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SEDIMENT TRANSFER ALONG MACKENZIE RIVER: A FEASIBILITY STUDY

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Canada

Western and Northern Region
IWD-WNR(NWT)-WRB-SS-87-1

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November 1986

NOTE TO READERS

This report was prepared by M. Miles and Associates Ltd. under contract to the Sediment Survey Section, Water Resources Branch. Funding was provided by the Water Planning and Management Branch of Western and Northern Region, Regina.

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T.J. Day
December, 1986

ACKNOWLEDGEMENTS

The authors would like to thank the following individuals for their assistance during the course of this project:

Mr. J. Anderson	National Hydrology Research Institute, Ottawa
Dr. T. Day	Sediment Survey of Canada, Ottawa
Mr. D. Dobson	Canadian Hydrographic Service, Sidney,
Mr. R.A. Halliday	Water Planning and Management Branch, Edmonton
Mr. C.P. Lewis	B.C. Ministry of Environment, Victoria
Mr. R. McClennan	Public Works Canada, Edmonton
Dr. E.B. Peterson	Western Ecological Services Ltd., Victoria
Mr. R. Tingley	Supply and Services Canada, Edmonton

Drafting and cartographic services were provided by Mr. B. Sawyer, B.F.A. and Mr. E. White, B.Sc. Technical assistance and report production were undertaken by Ms. E. Goldsworthy, B.Sc.

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LIST OF SYMBOLS

ΔA	net change in surface area of sediment stored in the reach
A_d	area of sediment deposited
$\bar{A}_d$	average area of sediment deposited per year
A_e	area of sedment eroded
$\bar{A}_e$	average area of sediment eroded per year
A_{dc}	corrected area of sediment deposited
A_{ec}	corrected area of sediment eroded
$\bar{a}_d$	average area of sedment deposited per metre of channel length per year
$\bar{a}_e$	average area of sediment eroded per metre of channel length per year
D_{10}	10 % of sediment analysed is finer than this value
D_{90}	90 % of sediment analysed is finer than this value
G_b	bed sediment transport rate
L_r	reach length
L_t	sediment travel distance
n	Number of samples
ΔS	net change in volume of sediment stored within the reach
S_d	volume of sediment deposited
S_e	volume of sediment eroded
S_i	sediment input
S_o	sediment output
S_t	sedment throughput (equivalent to "wash" load)

S_{dc}	corrected volume of sediment deposited
S_{ec}	corrected volume of sediment eroded
ΔW	change in channel width
W	wetted channel width
W_c	channel width (between vegetation trim lines)
W_i	mean channel width at low water (obtained from bathymetric charts
$\overline{W}_c$	mean channel width (between vegetation trim lines)
$\overline{W}_s$	mean channel width (including vegetated islands)
w	non-dimensinal width, = W/Wc
$X_{71\ i}$	average channel depth at low water (obtained from bathymetric charts), where '71' indicates the year of record and 'i' is the location (in river kilometres)
Δz	change in stage

1.0 INTRODUCTION AND OBJECTIVES

1.1 INTRODUCTION

Although it is one of the major rivers of North America, the remoteness of Mackenzie River has discouraged study of it. Hence, channel hydraulics and sediment transport remain poorly known. Proposed resource developments along the river and the desirability to develop a regional water management plan now require that knowledge of these phenomena be improved more rapidly than could be achieved by the expansion of conventional monitoring programs alone.

Information on sediment transport characteristics can be obtained from non-traditional sources. Specifically, historic planimetric and topographic surveys, aerial photographs and hydrographic sounding, supplemented with limited observations of sediment transport, might be used to construct an approximate sediment budget on a reach-by-reach basis.

In the long term, understanding the viability of alluvial ecosystems requires that the character of erosion and sedimentation be understood on a reach basis. It is appropriate to draw evidence from morphological and sedimentary studies, rather than just from sediment transport monitoring, because information of the appropriate character and resolution can be gained in that way. Net change within reaches - rather than total throughput of sediment - is critical for river stability. Further, it requires many years' monitoring, conducted at great expense, to establish the trend of river stability. Where map, chart, or air photo evidence is available, trends can be established from the observed pattern of changing morphology.

Some monitoring remains important in order to permit more detailed interpretation of net morphological changes in terms of a sediment budget.

The present project resulted from a request by Dr. T.J. Day, Head, Sediment Survey of Canada, to Professor Michael Church, at the University of British Columbia, to consider whether map and photo records could be used to obtain useful information on Mackenzie River. Because there is relatively little information available on the river, it is prudent first to undertake a feasibility study of the approach.

1.2 THEORY

The morphological character of Mackenzie River changes notably at certain places along its course, so that distinctive "reaches" may be defined. Some reaches are controlled by geology (Mackenzie River is not entirely an alluvial river), but most are delimited by major tributary junctions. "Reaches", in this discussion, are of order 100 km in length. Sediment delivered to Mackenzie River from some of the tributaries is distributed downstream in the main river, sorted, partly deposited, or exchanged with sediments resident along the river. This process produces the distinctive pattern of channel islands, fragmentary flood plain, and shifting channel bars. Changes in these features are associated with sediment transfer along Mackenzie River.

This situation has the following implications:

i) Sediment delivery to Mackenzie River from the tributaries (especially from the mountainous, left-bank tributaries) influences the morphology and behaviour of the main stem.

ii) Varying 'styles' of alluvial sedimentation occur along Mackenzie River (and in the tributaries), influenced by long-term sediment input and output, and by the texture of the sediment in each reach.

iii) Distinct alluvial ecosystems are associated with distinctive sedimentation styles, and these can be characterized on a reach-by-reach basis.

iv) Land use management - in the broad sense - in the tributary basins could influence the behaviour of Mackenzie River.

Our understanding of all of these situations will be improved if we can establish an approximate sediment budget for the river.

Consider a reach of a river (Figure 1.1). The sediment budget for the reach for an arbitrary time period can be written as

$$S_o = S_i + \Delta S \qquad (1\text{-}1)$$

where S_o and S_i are the sediment output and input respectively and ΔS, the net change in sediment stored within the reach, is the result obtained from the morphological studies. We can divide ΔS into the difference between erosion (S_e) and deposition (S_d)

$$\Delta S = S_e - S_d \qquad (1\text{-}2)$$

where these data are <u>net</u> for the time period. If sediment transport is monitored at the downstream end of the reach, so that S_o is known, then we obtain S_i.

Since S_i for the reach in question is S_o for the next upstream reach, we may extend the calculations upstream without resort to further monitoring. Furthermore, we may now obtain, for each reach, a quantity S_t, the sediment throughput:

$$S_t = S_o - S_e = S_i - S_d \qquad (1\text{-}3)$$

S_t corresponds to the traditional concept of 'wash load' in sediment transport studies (the material which, once entrained, travels all the way through the reach without being redeposited);

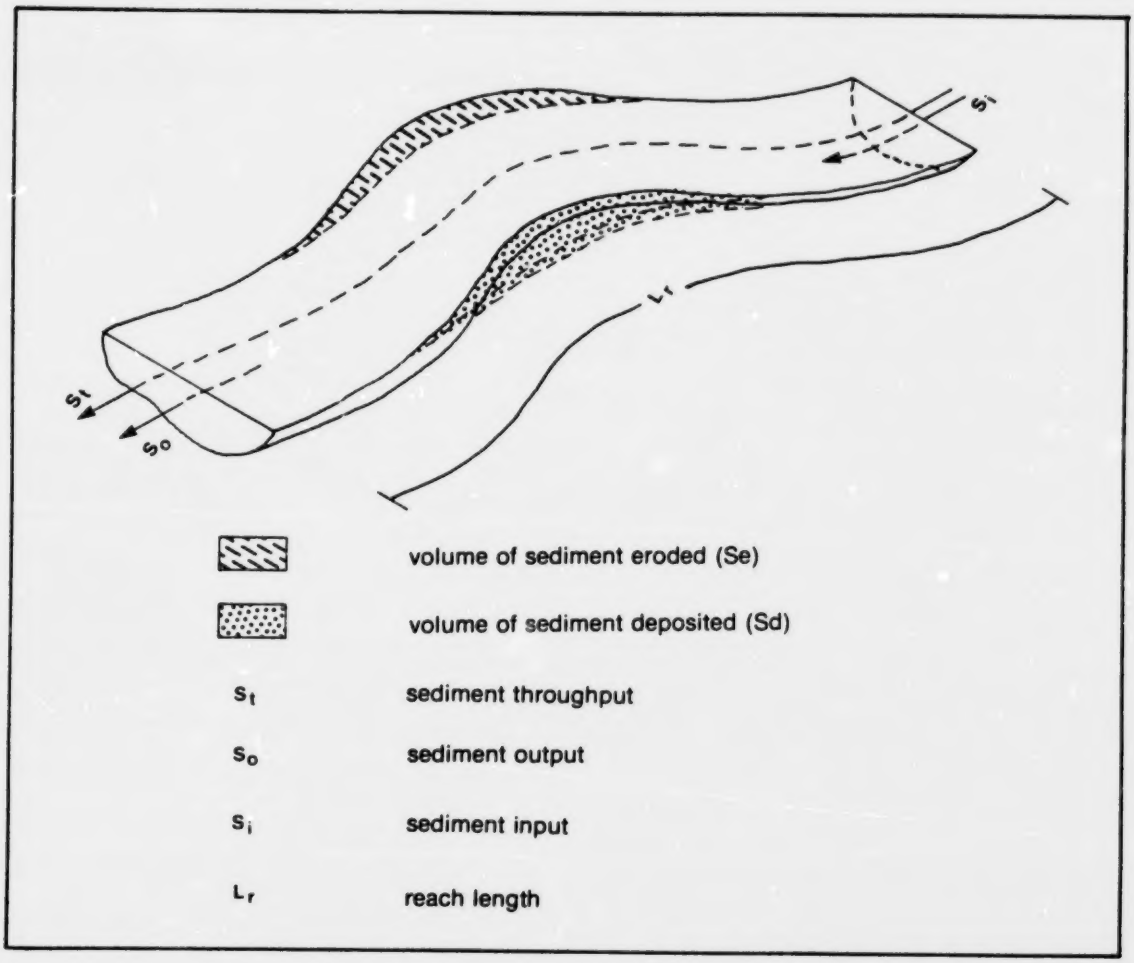

Figure 1.1: Schematic sketch of a river reach, showing the main sediment transfer components.

the balance of the sediment - that part involved in erosion and deposition within the reach - is obviously the bed material load, S_b. It is the latter which is of main interest in channel stability and alluvial ecosystem characterization.

There are some limitations in this method of constructing a reach sediment budget. Erosion and deposition are net for the time period: any material deposited and then re-entrained within the period will be counted as throughput. This factor is rather important on an annual basis in Canadian rivers which have a strong nival flood (of which Mackenzie River could serve as a type example). Further, where morphological information is available only once every few years, the record of sediment stored for shorter periods is lost. In general, morphological information must be gathered at the time scale of finest desired resolution of change.

ΔS may be very small in comparison with S_t. Indeed, if a reach is neither aggrading nor degrading, ΔS must become zero at some time scale, when $S_t = S_o = S_i$. The usefulness of the method to detect local aggradation or degradation is predicated on the notion that this time scale may be rather long in some rivers. For a river of the size of Mackenzie River, it could be many decades. However, net S_e and S_d may remain considerable if channel shifting occurs (as implied in Figure 1.1), so that the eroded sediment volume is partly or entirely distinct from the deposited volume. Then lower bound estimates of bed material transfer may still be made, and the rate of creation and destruction of alluvial foreshore and backshore habitat may be measured.

There remains the problem of error in measurements, which could be similar in size to S_e, S_d or ΔS. This would make upstream extension of calculations difficult. In general, an upstream station with sediment transport data provides a useful check on results. In any event, where a tributary introduces a significant additional load of sediment into the channel, there must be an independent assessment of that contribution.

Different size grades of sediment behave differently in the river. For example, in Mackenzie River, gravel will have S_t values approaching 0 per cent, silt and clay will have S_t values approaching 100 per cent, and sand will fall between these extremes. If grain size information is available along the river and from sediment transport monitoring, a further breakdown of the sediment budget is possible which may allow some control to be maintained over error propagation.

It is possible to make a further estimate of bed material transfer if some additional information is known. Neil (1971) showed, with respect to a regularly meandered river, that bed material transfer may be approximated by:

volume eroded per unit length of channel x distance of transfer

The meander pattern indicates the distance of travel on the assumption that material eroded from one bend is deposited on the next downstream bar. The meander half-wavelength then gives the travel distance. The concept may be extended to less regular channels provided there is some morphological evidence for the sediment travel distance. In our notation, the bed sediment transport rate G_b is S_e/t or S_d/t, for the time period t, if the travel distance, L_t, is the same as the reach length, L_r. Otherwise,

$$G_b = (S_e/t)(L_t/L_r) = (S_d/t)(L_t/L_r) \qquad (1\text{-}4)$$

1.3 OBJECTIVES

As discussed in the original terms of reference the objectives of this feasibility study are to carry out the following tasks:

Task 1 Review and Summary of Prior Studies of Sedimentation along the River.

Several syntheses of hydrological and sedimentation data on Mackenzie River have been carried out in recent years. Most of the work was commissioned for government agencies

and is not widely available. Before commencing new work, it appears prudent to consider these results.

Task 2 Appraisal of Hydrographic Charts:

These are potentially the major source of information. Location of available information, review of individual chart precision, and review of navigation (which will determine the possibility to make chart-to-chart comparisons) will be undertaken.

Task 3 Appraisal of Air Photograph Records

Air photographs have been flown over the river relatively frequently, but not annually. However, the records would permit extension of the study back through a period of about 40 years if some simple planimetric/volumetric correlations can be determined for sediment bodies, and if water level adjustments can be made. This appears to be worth preliminary investigation.

Task 4 Test Evaluation of Sediment Transfers in One Reach from Chart and Air Photo Records:

This represents the main work to be undertaken and will be designed to answer the question of whether changes in sediment deposits can be resolved satisfactorily. The test area will be the 190 km reach from Great Bear River to Mountain River (Sans Sault Rapids). This is a mainly anastomosed reach in which there are relatively large changes in island and bar positions. In the vicinity of Norman Wells, there may be additional air photograph coverage and river bed information available due to the oil exploration work that has been conducted in this area.

Task 5 Evaluation of Sediment Transport Data to Permit Sediment Budget Construction, and Preliminary Consideration of Unmonitored Tributaries:

This work is designed to determine whether the available data are sufficient to permit sediment budgets to be recovered for the river, or for certain reaches.

Task 6 Report Preparation:

The report will be brief and will be designed to indicate the feasibility of the proposed main study, rather than to present definitive results.

2.0 AVAILABLE INFORMATION

2.1 INTRODUCTION

The compilation and assessment of relevant data is one of the major objectives of the feasibility study. The following sections provide a brief description of the available material. Section 2.5 reviews prior studies of sedimentation (Task 1).

2.2 HYDROMETRIC AND SEDIMENT DATA

The locations of active and discontinued Water Survey of Canada gauging stations in the lower Mackenzie River basin, which provide data relevant to this study, are shown on Figure 2.1. Station descriptions, based on the Water Survey of Canada Station Numbers, can be found in Inland Waters Directorate (1983). The monitoring program conducted at stations providing sediment data relevant to the Great Bear River to Mountain River Test Reach is summarized in Table 2.1.

Suspended sediment and bed material size data collected at the monitoring stations shown in Table 2.1 and on Figure 2.1 were obtained from the Sediment Survey of Canada for detailed analysis. These data conform with the usual standards for the Sediment Survey of Canada, as described in Inland Waters Directorate (1984). The extent of the data is given in Table 2.2.

2.3 HYDROGRAPHIC INFORMATION

The Canadian Hydrographic Service is responsible for undertaking bathymetric surveys of Mackenzie River. A portion of these data is available on published charts. However, the actual field sheets contain far more information. Copies of all historic field sheets were therefore obtained from the Canadian Hydrographic Service. The years in which field data are available were

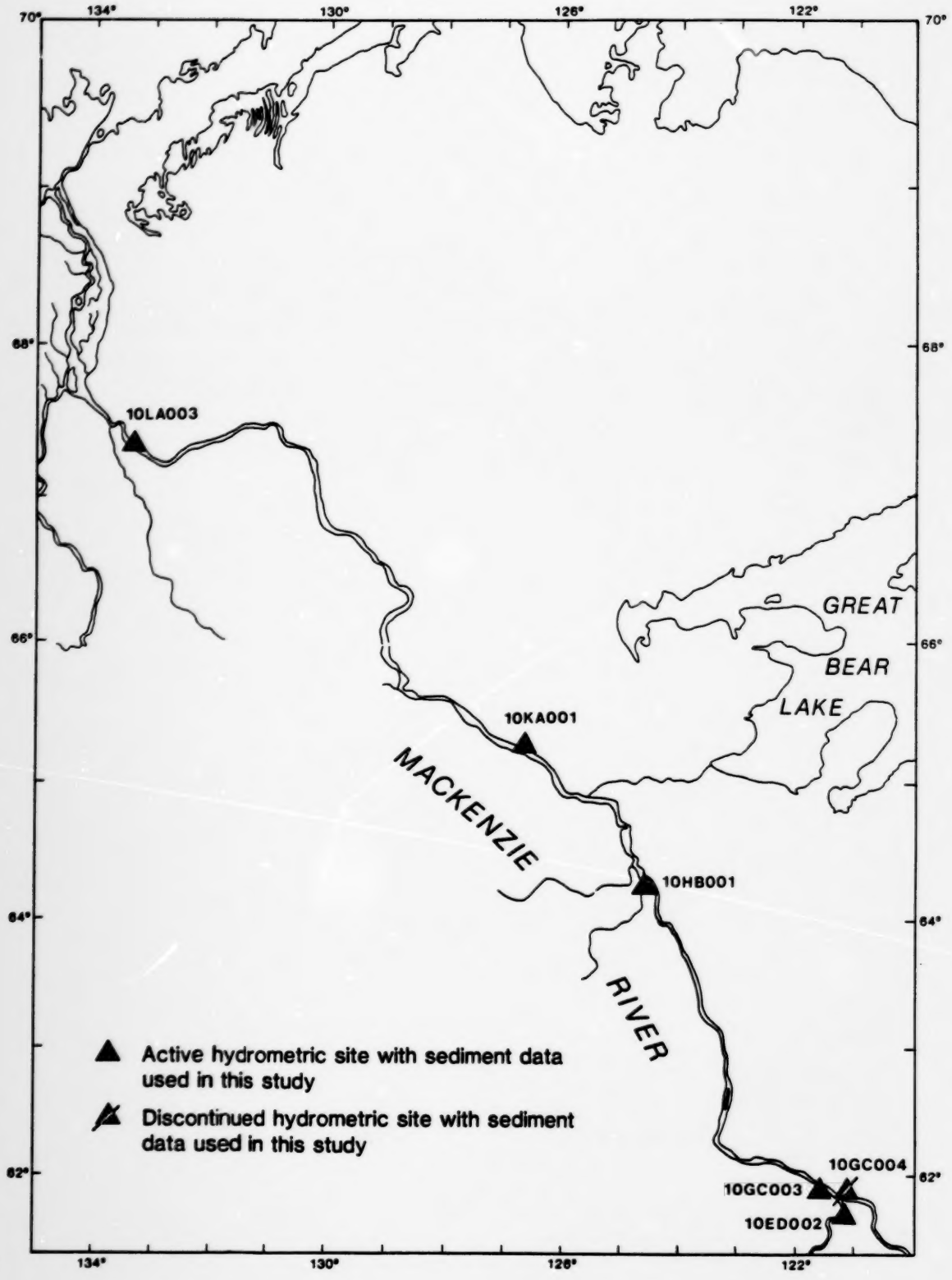

Figure 2.1:
Location of hydrometric stations used in this study (after Inland Waters Directorate, 1977)

TABLE 2.1: Sediment Monitoring Stations Providing Data Relevant to the Present Project (from Inland Waters Directorate, 1983 and 1984).

BRITISH COLUMBIA

STATION	NAME	DRAINAGE AREA (km^2)	GAUGE LOCATION	DISCHARGE PERIOD	RECORD TYPE	SUSPENDED SEDIMENT: SEDIMENT YIELD	SUSPENDED SEDIMENT: TYPE OF OBSERVATION	SUSPENDED SEDIMENT: PARTICLE SIZE DI	BED MATERIAL PARTICLE SIZE	REMARKS
10ED002	LIARD RIVER NEAR THE MOUTH	227000	61 44 50 121 13 25	72 - 83	RC	1972 1973-74 1975 1976 1979-82	M* MS M* MS MS	1972 1973-73 1976 1979-82	1973-74	NAT 3
10GC003	MARTIN RIVER NEAR THE MOUTH	2040	46 53 10 121 37 05	72 - 83	RC	1973-74 1975 1976	MS M* MS	1973-74		NAT 3
10GC004	MACKENZIE RIVER ABOVE LIARD RIVER	--	61 52 00 121 20 00			1972-74# 1975	MS M*		1974	REG 68 1,3

R - RECORDING GAUGE
M - MANUAL SAMPLING
C - CONTINUOUS OPERATION
S - SEASONAL OPERATION

& - WATER LEVEL ONLY
# - CONCENTRATION DATA ONLY
1 - DATA NOT PUBLISHED
3 - WATER TEMPERATURE DATA AVAILABLE

* - MISCELLANEOUS DATA ONLY
NAT - NATURAL FLOW
REG - REGULATED FLOW SINCE 19..
(YEAR SHOWN IF KNOWN)

NOTE: No point integrated suspended sediment particle size data, bed load volumes or bed load particle size data are available.

TABLE 2.1: (cont'd)

STATION	NAME	DRAINAGE AREA (km^2)	GAUGE LOCATION	DISCHARGE PERIOD	RECORD TYPE	SUSPENDED SEDIMENT: SEDIMENT YIELD	SUSPENDED SEDIMENT: TYPE OF OBSERVATION	SUSPENDED SEDIMENT: PARTICLE SIZE DI	BED MATERIAL PARTICLE SIZE	REMARKS
10HB001	REDSTONE RIVER NEAR THE MOUTH	15400	63 55 37 125 18 07	63 - 64 65 - 70 71 - 83	RC RS RC	1973	M*	1973		NAT 1,3
10KA001	MACKENZIE RIVER AT NORMAN WELLS	1570000	65 16 54 126 50 58	43 - 56 60 - 61 62 - 78 79 - 83	MS M& RC RS	1973	M*	1973		REG 68 1,3
10LA003	MACKENZIE RIVER ABOVE ARCTIC RED RIVER	1660000	67 21 30 133 33 30	72 - 83	RC	1972 1973-74 1975 1980-82	M* MS M* MS	1972 1973-7 1975 1980-8	1972 1973-74 1975	REG 68 3

R - RECORDING GAUGE
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NAT - NATURAL FLOW
REG - REGULATED FLOW SINCE 19..
(YEAR SHOWN IF KNOWN)

NOTE: No point integrated suspended sediment particle size data, bed load volumes or bed load particle size data are available.

TABLE 2.2: Summary of Suspended Sediment and Bed Material Samples Relevant to the Present Project.

STATION	NAME	YEAR	# OF SUSPENDED SEDIMENT MEASUREMENTS		# OF BED MATERIAL PARTICLE SIZE MEASUREMENTS
			CONCENTRATION	PARTICLE SIZE	
10ED002	LIARD RIVER	1972	5	4	
	NEAR THE	1973	67	23	
	MOUTH	1974	42	7	11
		1975	9	—	6
		1976	33	3	
		1977	--	--	
		1978	--	--	
		1979	43	4	
		1980	30	5	
		1981	15	5	
		1982	20	(?)	
10GC003	MARTIN RIVER	1973	A		
	NEAR THE	1974	A	1	
	MOUTH	1975	A	2	
		1976	A		
10GC004	MACKENZIE	1972	5	—	
	RIVER ABOVE	1973	27	--	
	LIARD RIVER	1974	21	—	8
		1975	9	--	
10HB001	REDSTONE RIVER NEAR THE MOUTH	1973	A	5	
10KA001	MACKENZIE RIVER AT NORMAN WELLS	1973	A	6	
10LA003	MACKENZIE	1972		2	4
	RIVER ABOVE	1973	27	11	14
	ARCTIC RED	1974	30	2	7
	RIVER	1975		2	7
		1980		7	
		1981		4	
		1982		(?)	

A - Data available but not published

? - Inland Waters Directorate (1984) indicates samples were anlaysed, however the computer listings supplied by the Sediment Survey Section do not show any 1982 data.

determined for each of the published map sheets. This data compilation is included as Appendix I.

The locations of relevant Canadian Hydrographic Service charts, and the years in which field surveys were conducted, are summarized on Figure 2.2. This figure indicates that bathymetric data generally are limited to two or three surveys undertaken in the 1970s. Exceptions occur in the vicinity of Sans Sault Rapids, where additional detailed mapping (1:7,200) is available for 1958 and in the Fort Norman - Norman Wells area where 1:65,000 scale mapping is available from 1964. The 1970 vintage mapping available throughout the area from Great Bear River to Point Separation is at a scale of 1:50,000.

2.4 AERIAL PHOTOGRAPHS

All available indices of relevant federal aerial photographs were identified on the basis of published catalogues (Canada Dept. of Energy Mines and Resources, 1974, et seq.). These air photograph indices were obtained from the National Air Photograph library. A compilation was then made of all photography available for the 190 km section of Mackenzie River located between Great Bear River and Mountain River. This summary, shown in Appendix I, includes the year of photography, photograph scale, index number, and comments on the location of the flight lines.

These data indicate that photographic coverage extends back as far as 1944. Much of the available photography is of relatively large scale (i.e. >1:20,000) and therefore provides better resolution than the hydrographic charts which generally have a scale of 1:50,000.

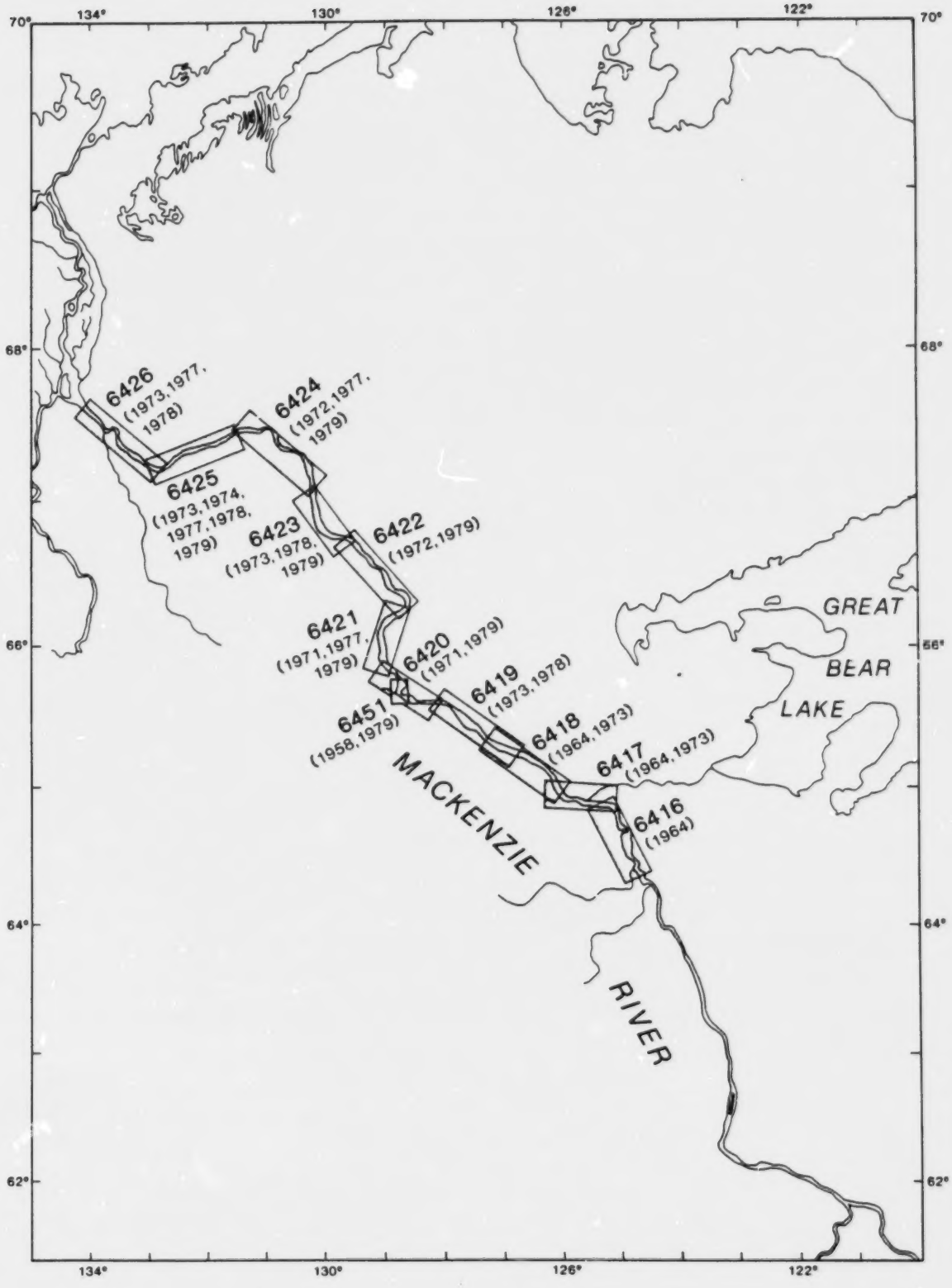


Figure 2.2:
Location of Canadian Hydrographic Service charts of lower Mackenzie River showing years in which field surveys were undertaken (after Canadian Hydrographic Service, 1985)

2.5 PRIOR STUDIES OF SEDIMENTATION

There are in effect no studies of alluvial sedimentation along Mackenzie River. An analysis of the suspended sediment yield from the basin has been made by Lewis (in press), mainly on the basis of observations at Station 10LA003 (Mackenzie River above Arctic Red River): it is of order 10^8 tonnes per annum. In work for the Mackenzie River Basin Committee (1981c: Part 2; pp. 124-202) Grey has analyzed the regional sources of the sediment load.

In the upper Mackenzie basin, only the Liard drainage is not controlled by large lakes, so that it is the source of most sediment input to the main stem. Within the Liard basin, the Fort Nelson-Muskwa-Prophet River system was identified as a major sediment source. Short records and paucity of measurement sites prevent any definitive statements being made, but it appears that the upper Liard River proper is of comparable importance. Farther down Mackenzie River, the unregulated western tributaries and the banks of Mackenzie River are the main additional sediment sources. Both the Liard basin and the western tributaries, which drain the Mackenzie Mountains, are subject to locally severe summer storms which may generate major floods and sediment yield (Smith, 1975; Mackay, et al, 1973; Sherstone, 1983). Such storms are relatively rare and do not influence the entire basin. However, the pattern of regional sediment yield may vary substantially from year-to-year.

Several studies have examined bank stability along Mackenzie River (cf. Chyurlia, 1973; Code, 1973; McRoberts and Morgenstern, 1973), but no estimates have been made of quantitiative sediment yield rate to the river.

In a report to the Mackenzie River Basin Committee (1981c, part 5), Fox presented a preliminary study of sites of alluvial erosion and sedimentation along Mackenzie and Liard Rivers. Qualitative air photo comparisons were used to identify sites of interest. He noted that water level changes between successive

photos is a major impediment to quantitative interpretation. He also noticed that whereas channel banks and well-vegetated islands did not change significantly, in general, over 30 years, river bars changed substantially in reaches with active sedimentation. The major task of the present report is to determine whether sufficient information exists to measure these changes, hence to compute sedimentation.

Northwest Hydraulic Consultants (1979), in a proprietary report for Esso Resources Limited which has, however, been released to the Canadian government (cf. Inland Waters Directorate, 1985), made estimates of hydraulic conditions, sediment transport and channel stability in a reach of the river in the vicinity of Norman Wells. They concluded that bed material transport may be on the order of 750,000 tonnes/year. The basis for the estimate - map and air photo studies and comparison with available information from other stations - was similar to that employed in this study, although considerably more restricted. Accordingly, this is a helpful reference figure.

Alluvial ecosystems along Mackenzie River have been discussed in Mackenzie River Basin Committee reports (1981a; 1981b). Aside from the major deltas, they are restricted mainly to channel islands and fragmentary flood plain areas. Erosion and deposition of sediment by the river continuously destroys and recreates a portion of this habitat, maintaining areas of successional vegetation development and the high habitat diversity that accompanies such continuous change. Sedimentation patterns have been discussed for several sites on the basis of reconnaissance stratigraphical investigations by Hardy and Associates (1982) in a proprietary report to British Columbia Hydro and Power Authority. Again apart from the deltas, these represent the richest habitats in Mackenzie basin. It therefore seems important to understand the sedimentological basis for their maintenance.

3.0 METHODOLOGY

3.1 ANALYSIS OF SEDIMENT DATA

It was pointed out in Section 1.2 that only part of the sediment load in the river comprises bed material. It is a useful preliminary exercise to attempt to determine the size range of alluvial bed material and of wash load. In order to accomplish this, grain size data from suspended sediment and bed material samples collected by the Sediment Survey of Canada were plotted and compared.

Bed material data are scarce and of uneven quality because of sampling difficulties. Useable data from Stations 10LA003 (Mackenzie River above Arctic Red River), 10AC004 (Mackenzie River above Liard River) and 10ED002 (Liard River near the Mouth) have been selected. The chief reasons for rejecting bed material data are:

i) inadequate sample recovered (too little material);
ii) obviously non-alluvial bed; or
iii) no comparable suspended sediment texture data available.

Data were plotted for comparison on a seasonal basis, and only samples taken within the same year were compared directly.

There is essentially no suspended sediment in excess of 2 mm. Hence, comparisons have been made with bed material size distributions truncated at 2 mm (Appendix II). For comparison, complete bed material size distributions have also been plotted (Appendices III and IV). Bed material larger than 2 mm may have one of several origins:

(a) bedload (particularly likely near the major western tributary confluences);

(b) ice rafted material derived from non-alluvial banks; or

(c) non-alluvial material in situ (it is possible that neither main stem sediment observation station is alluvial in the present regime).

First, size distribution of suspended sediment is compared along the river (Figure 3.1) for 1973, the only year for which there are data at Norman Wells. (All available data are plotted in Appendix II.) The distribution is relatively uniform along the river, but apparently persistently finer at the downstream station Mackenzie River above Arctic Red River (10LA003). The results at this site are confirmed in 3 other years of record (Appendix II).

Comparison of suspended sediment texture with truncated bed material texture was effected by examining the median values of grain size for D_{10} (i.e. 10 per cent of bed material is finer than this size) and D_{90} (90 per cent of suspended material is finer).

The 'median' referred to is the median of relevant samples. The values were estimated by inspection of cumulative grain size diagrams showing all analyses for each station in each year (Appendix II). Results are given in Table 3.1.

The 10 per cent criterion from end-of-range was used in order that the possibilities for wash material to be trapped in the bed, and for saltating material to be caught near the bed during suspended sediment sampling, should not unduly affect the results. At Station 10LA003 (Mackenzie River above Arctic Red River), the sand-silt break (0.062 mm) appears to define the distinction between wash load and bed material rather well, except in 1972 (the limit may change seasonally or over several years). Upriver, the distinction appears to fall between 0.1 and 0.2 mm. Figure 3.2 illustrates the range of available suspended and bed material samples over all years.

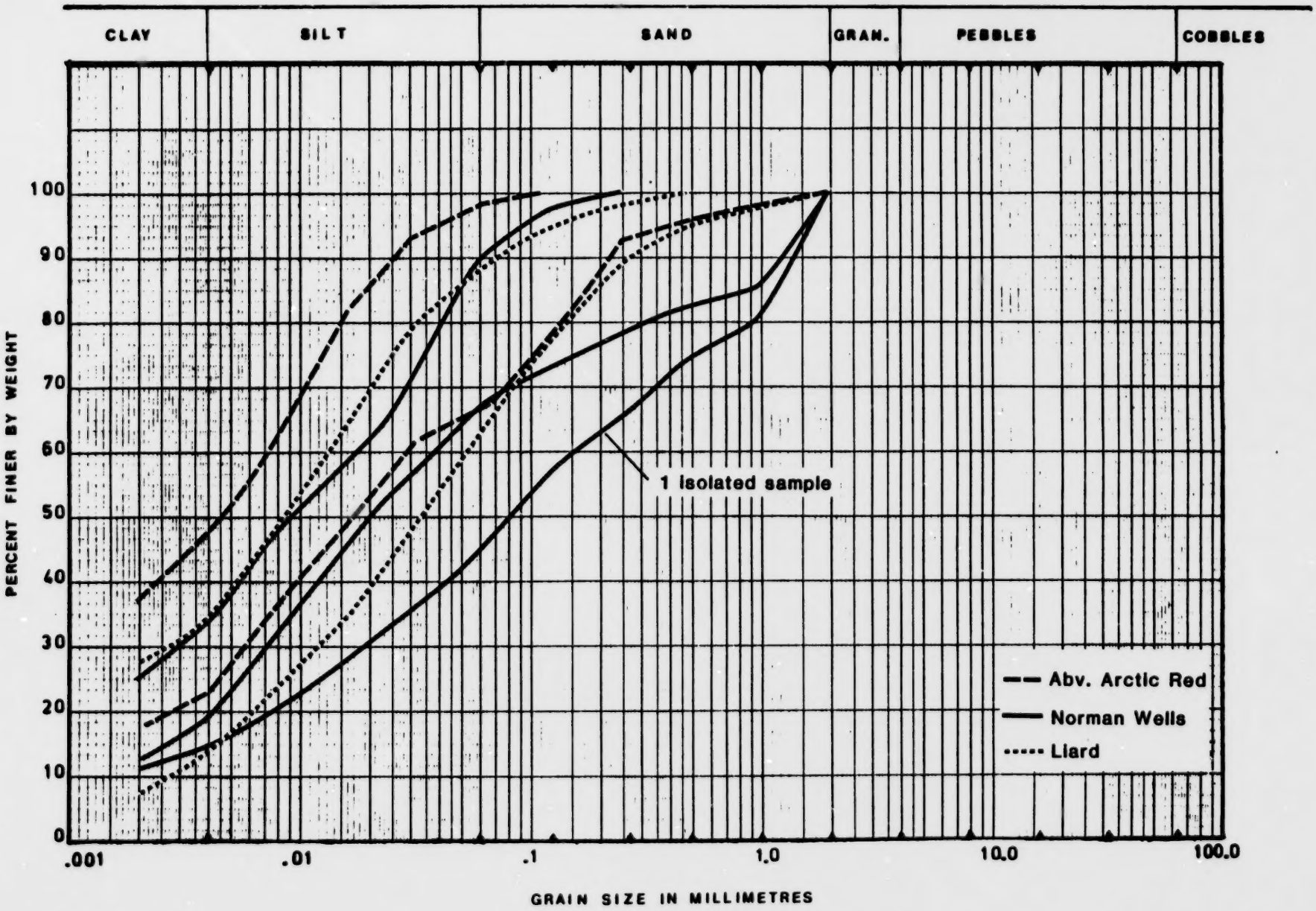


Figure 3.1:
Range of suspended sediment size distributions: 1973

TABLE 3.1: Median limit sizes for suspended and bed material

STATION	YEAR	D_{90} suspended (mm)	D_{10} bed (mm)
10LA003	Mackenzie River above Arctic Red River		
	1972	0.140	0.150
	1973	0.050	0.062
	1974	0.062	0.080
	1975	0.048	0.090
10ED002	Liard River near the mouth		
	1973	0.140	0.090
	1974	0.200	0.200
10KA001	Mackenzie River at Norman Wells		
	1973	0.175	

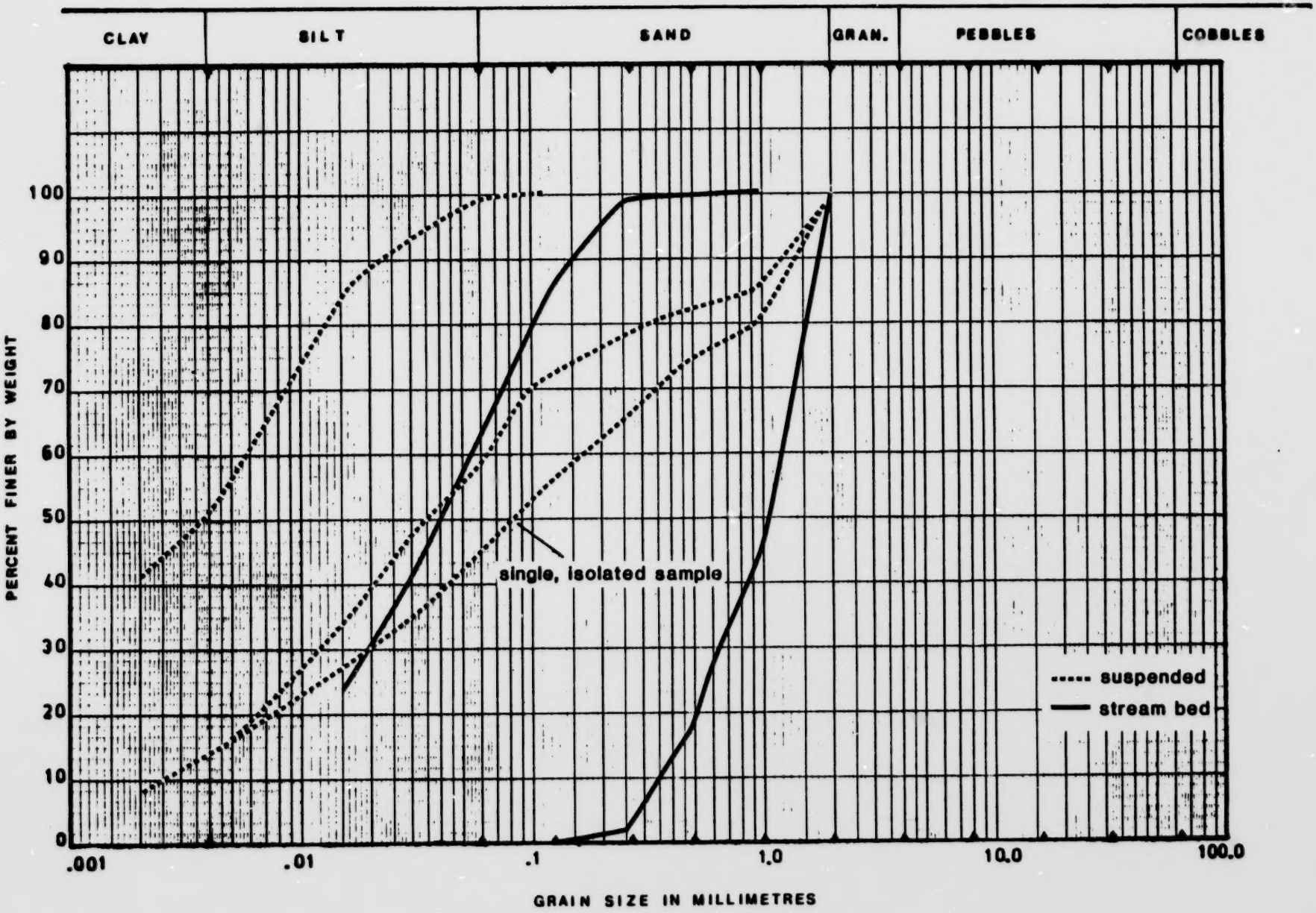


Figure 3.2:
Range of suspended and bed material sizes.

Northwest Hydraulic Consultants (1979) noted that, for the range of flows in Mackenzie River, the hydraulic criterion for bed sediment to be lifted into suspension constrained suspended material to be less than about 0.2 mm, which is in agreement with the sample textures. It appears then, that wash load corresponds approximately with suspended sediment load, and that the bulk of bed material transfer occurs as bedload.

A more determined investigation would require a better definition of bed material size than present results permit. We conclude that bed material in Mackenzie River above Sans Sault is delimited by about 0.15 mm. Downstream it has a lower limit near 0.062 mm.

3.2 MAPPING FROM AIR PHOTOGRAPHS

Planimetric mapping of Mackenzie River, based on historical air photographs, was compiled for the 85 km reach between Ten Mile Island and Patricia Island, upon which Norman Wells is located. Mapping was undertaken at a scale of approximately 1:25000. Three planimetric maps were compiled from photography flown in 1950 - 1951, 1961 - 1962, and 1971.

This mapping was completed to allow exact comparison of the relative positions of banks, waterlines, bars and islands of the Mackenzie River between 1950/51, 1961/62 and 1971. There are a variety of ways to accomplish this task. Within the constraints of the project, the best approach was to use the 1961/62 photography to produce a base map and then to use control established during the base mapping to match the 1950/51 and 1971 aerial photography to the base map. It should be noted that the NTS 1:50,000 topographic mapping of this area (96E/1,2,5,6,7,12) is based on 1950-53 photography. Because of the apparently variable conventions employed by cartographers in delineating river banks and bars, these maps were not adopted for use in the comparison exercise.

The base map was produced by a procedure called "uncontrolled extension". The advantage of this procedure is that it allows rapid planimetric mapping from a large number of photographs without reference to external survey control. The disadvantage of the procedure is that the mapping may not reflect the actual horizontal location of the different features. As mapping proceeds upriver or downriver from Norman Wells, small angular deviations are introduced between successive photogrammetric models (photo pairs) which may twist the map of the river relative to its true position. These deviations are generally small over the entire mapped reach and have no effect on the comparison of planimetry from 1950/51 and 1971 with the base map. Short reaches of channel, within which comparisons are made, remain essentially undistorted.

The initial model for mapping -- the area around Norman Wells -- was scaled down to 1:25000. Mapping proceeded upriver and downriver from this point. The adjacent model was scaled and oriented to control passed from this initial model; the next model was scaled and oriented to the second model, and so on.

Accurate and undistorted planimetry from each photo-pair requires only that the photo-pair be approximately level (relative to geodetic datum) during mapping. This was accomplished by using the water surface of the Mackenzie River to level the model both parallel and perpendicular to the direction of flow. The river gradient is insufficient to introduce any detectable error into this procedure. During production of the base map the location of natural and man-made features such as lakes, gullies and road intersections, which were suitable photo control points, were marked on the base map. These points were also marked on the 1950/51 and 1971 photography.

The following information was compiled on the maps:

1. **reference bank location:** An easily identifiable bank position was marked on both the west and east sides of the channel. The reference varied from reach to reach. The marked position is either a cliff top, a break slope below the cliff top, or the edge of permanent vegetation.

2: **water line:** The horizontal positions of all water-lines are marked on the map.

3: **vegetation boundaries:** Two boundaries are marked: the edge of mature (forest) vegetation and the edge of immature (shrub) vegetation. The shrub boundary is only approximate due to difficulties in distinguishing between shrubs and "wet" bar surface on some photographs.

The 1950/51 and 1971 maps were produced by the following procedures:

1: Control points were transferred from the 1961/62 photography to the 1950/51 and 1971 photography. At least four control points were marked on each photo-pair for the 1950/51 and 1971 photography.

2: The location of the control points was transferred from the base maps to separate mylar compilation sheets for each year of photography.

3: Each photo-pair was scaled and adjusted to exactly match the control on the photography to that on the mylar map compilation sheet.

4: Each photo-pair was levelled using the water surface of the Mackenzie River.

5: Planimetry was compiled for each photo-pair.

The same information was compiled for the 1950/51 and 1971 photography as for the base map.

The principal limitations on the accuracy of the between year comparisons are:

1: The accuracy of transferring points from the 1961/62 to the 1950/51 and 1971 photography.

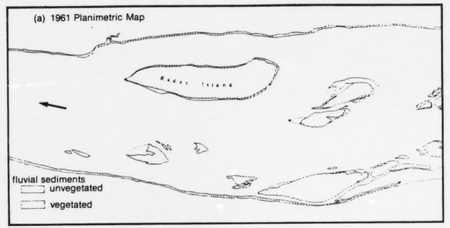
2: The accuracy of adjusting the 1950/51 and 1971 photography to the base sheet.

3: The accuracy of mapping the planimetry.

Most of the inaccuracy is probably associated with Point 1. It is expected that variation due to these sources of inaccuracy should amount to less than 0.5 mm (12.5 m at map scale) within any given reach. Special conditions may produce larger errors in certain areas.

3.3 PLANIMETRIC MAP ANALYSIS

Since the maps were produced to common control taken from the 1961-62 photography, superimposition is a simple matter. This was done and new maps were drawn showing areas of apparent sediment deposition between successive mappings (exposed bar surface present at the later date, but absent at the earlier date), and of apparent erosion (flood plain, valleyside or bar area present at the earlier date and absent at the later one). Waterline position was the discriminating criterion. Hence, these do not represent absolute changes, since stage differences between the successive dates of photography will produce a false impression of erosion (higher stage at later date) or deposition (lower stage at later date) along the river. Figure 3.3 gives an example.



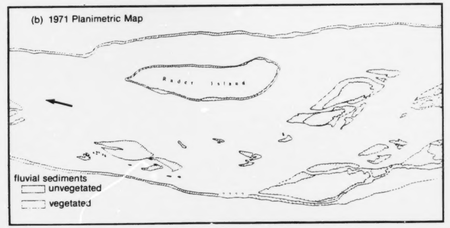


Figure 3.3 a & b: Planimetric maps for (a) 1961 and (b) 1971 for km 33-41 of the test reach (see Figure 4.3 for location). By overlaying the two maps a composite (c) is drawn identifying areas of apparent degradation (erosion) and apparent aggradation (deposition).

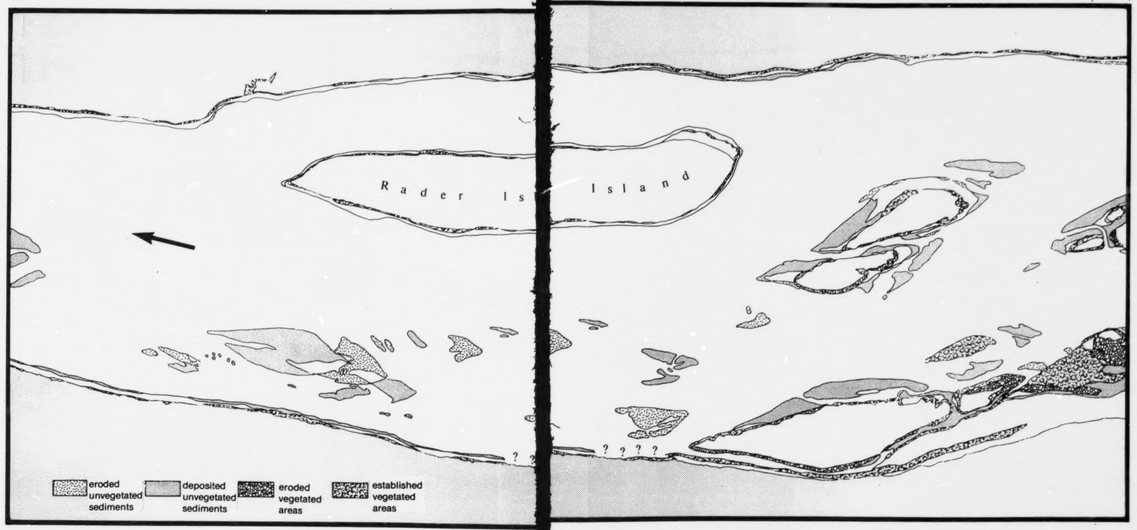


Figure 3.3c Planimetric Map showing areas of change from 1961 to 1971

The area of apparent sediment deposition and the area of apparent erosion were planimetered from the composite maps for 1951-1961 and 1961-1971 by 2 km units along the river in the selected test reach (Section 4.1). The data were corrected to estimate actual deposition and erosion by application of a depth-area curve for the river (hypsometric curve) derived from bathymetric data (Section 3.4), and Norman Wells stage data for the dates of photography. The basis for the adjustment is as follows:

- suppose the reach has a mean channel width $\bar{W}_c$ between vegetation lines, with individual segments summed for a divided channel;
- the hypsometric curve yields an exposure gradient dw/dz, which we express as a proportional change in width per metre change in depth;
- the reach has length L_r

Then

$$L_r \cdot \bar{W}_c \cdot \frac{dw}{dz} \cdot \Delta z \qquad (3\text{-}1)$$

is the areal change in exposure in the reach due to stage change. The mean channel width, W_c, provides the appropriate length dimension for the proportional change dw. Considering the stage change (Δz) as an algebraic quantity (positive for stage rise) corrected depositional area (A_{dc}) is:

$$A_{dc} = A_d + L_r \cdot \bar{W}_c \cdot \frac{dw}{dz} \cdot \Delta z \qquad (3\text{-}2)$$

and corrected erosional area (A_{ec}) is:

$$A_{ec} = A_e - L_r \cdot \bar{W}_c \cdot \frac{dw}{dz} \cdot \Delta z \qquad (3\text{-}3)$$

Figure 3.4 shows the principle for a simple case. This a crude adjustment as:

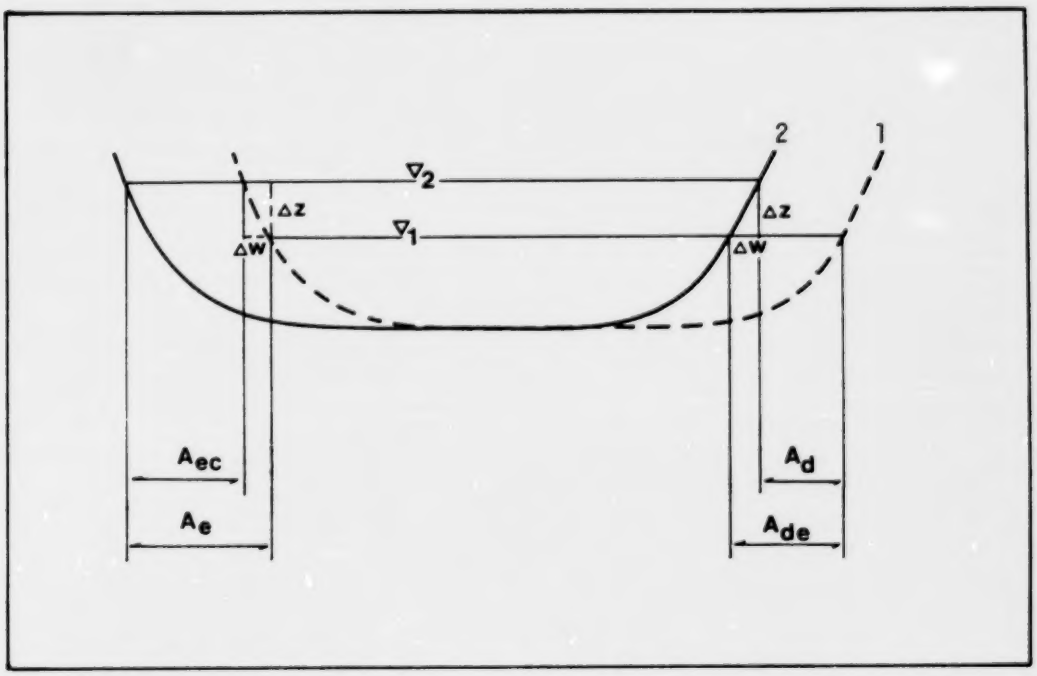
i) variations in channel form; and
ii) the possibility for water depth and flow velocity to adjust mutually to changes in water discharge

may cause the stage change for a given change in flow to vary along the river. The data in hand are insufficiently detailed to warrant more detailed corrections. In a definitive application of the methods being explored here, specific gauge information could be developed, with limited field work, for many places along the river.

Table 3.2 gives the river stage at Norman Wells on the dates of photography. Details of the required corrections are taken up again in Section 4.2.

Once the areas of deposited and eroded sediments are available, these values can be multiplied by the depth of mobile sediments and divided by the number of years over which changes in channel position were documented in order to estimate the average annual volume of deposited or eroded sediments (S_{dc} and S_{ec}) within the reach. This then allows the bed material transport rate (G_b) to be calculated on the basis of equation 1-4. Alternatively, the area of eroded and deposited material (A_{ec} and A_{dc}) can be divided by the reach length and the number of years over which changes in channel position were documented to yield an estimate of average bank recession or progradation per metre of channel. Knowing the depth of mobile sediments and the sediment transport distance (L_t) allows the calculation of the bed material transport rate (G_b).

The planimetric exercise was repeated for the change in vegetated bar surface, to express the change in riparian alluvial habitat. In this exercise, corrections were not applied. Results may be in error to the extent that low growth may be drowned at high stage and not discernable in photos taken at that time.



Note: The river has migrated to the left from early (1) to later (2) time, but has not changed its shape. Ae and Ad represent apparent change in erosional and depositional areas. Aec and Adc are the actual areas after the change in water level (∇_1, to ∇_2) has been corrected for.

Figure 3.4: Principle of exposure adjustment for stage change.

TABLE 3.2: DATE OF AIR PHOTOGRAPHY AND RIVER STAGE IN TEST REACH

NOMINAL DATE	AIR PHOTO NUMBERS	FLYING DATE	NOMINAL SCALE 1:	STAGE (m) MACKENZIE RIVER AT NORMAN WELLS (10KA001)		DISCHARGE (m3/s)	MAPPING *1
1950-1951	A12586/ 340-341	07/06/50	40,000	3.81		7930	32-40
	A12587/ 246-247	09/06/50	40,000	3.94		8380	not used
	352-353	09/06/50	40,000	3.94		8380	not used
	A12575/ 292-293	09/06/50	40,000	3.94		8380	8-26
	317-318	09/06/50	40,000	3.94		8380	8-26
	A12590/ 43- 44	09/06/50	40,000	3.94		8380	0-14
	165-166	09/06/50	40,000	3.94		8380	0-14
	185-186	09/06/50	40,000	3.94		8380	26-32
	289-320	10/06/50	40,000	4.09		8860	not used
	A12602/ 47- 48	22/06/50	40,000	5.91		17400	36-60
	76- 77	22/06/50	40,000	5.91		17400	36-60
	194-195	22/06/50	40,000	5.91		17400	36-60
	A13305/ 308-310	15/07/51	40,000	5.54		15300E	60-72
1961-1962	A17496/ 137-144	15/09/61	40,000	4.51		10500	0-24
	147-154	15/09/61	40,000	4.51		10500	0-24
	A17800/ 1- 15	20/08/62	40,000		*2		24-76
	24- 27	20/08/62	40,000		*2		24-76
	36- 41	20/08/62	40,000		*2		24-76
1971	A22387/ 147-150	26/07/71	50,000	5.47		15000	32-50
	172-173	26/07/71	50,000	5.47		15000	not used
	181-182	26/07/71	50,000	5.47		15000	0-14
	A22388/ 13- 16	28/07/71	50,000	5.07		13100	12-30
	35- 37	28/07/71	50,000	5.07		13100	60-74
	A22474/ 92- 94	07/08/71	50,000	4.95		11600	52-62
	102-105	07/08/71	50,000	4.95		11600	not used

Note: 1. i.e. photos were used to map the reach km listed.
Add 880 km to obtain river kilometres.

2. see text Section 4.3

3.4 ANALYSIS OF BATHYMETRIC DATA

The only bathymetric survey to cover considerable reaches of the river within the time frame of our map comparisons is the 1971-1973 complete survey of the river. Figure 3.5 shows an example of the quality of information available from the field sheets. The hydrographic charts that were made from these data also displayed river morphology as interpreted from the 1971 air photography.

Using the 1972-1973 surveys, the following results were extracted for the test reach:

(i) cross-section at the midpoint of each 2-km measurement reach;

(ii) average depth and variation in depth in each 2-km measurement reach.

For the first result, plotted soundings were digitized. It can be seen in Figure 3.5 that the plot lines (following the sounding boat track) are not rectilinear across the channel. The plot line (or lines) that falls closest to the reach midpoint section was followed; no adjustments were made for divergence between the two. Figure 3.6 illustrates some results. From these data, the depth-area curves in the test reach were derived for the channel below low water (the reference datum for the bathymetric charts). To obtain a depth-area chart for the full depth of the channel (i.e. to bankfull), it would be necessary to obtain complete topographic cross-sections, which would require field surveys. For our purposes conjectural extension of the hypsometry was followed to the channel banks (as defined on the hydrographic charts) at +6.0 m relative to low water.

The second result was derived for the subreach between km 29 and km 65 by obtaining the mean of all plotted soundings in each 2-km unit. This exercise was repeated using the 1978 survey field

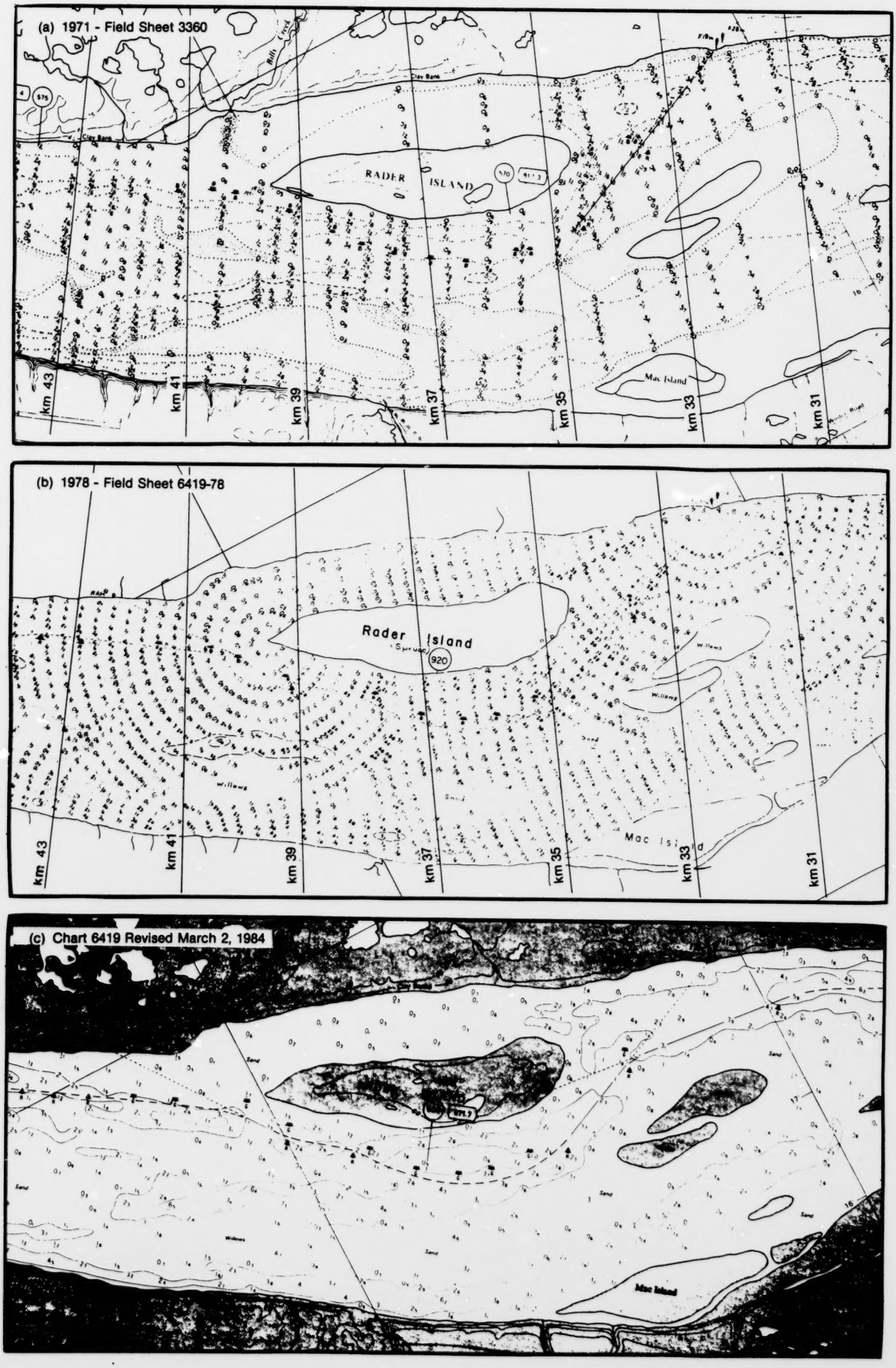


Figure 3.5: Extent of (a) 1971 and (b) 1978 bathymetric field sheets for the same reach as shown in Figure 3.3, and (c) the published chart of the same reach for comparison.

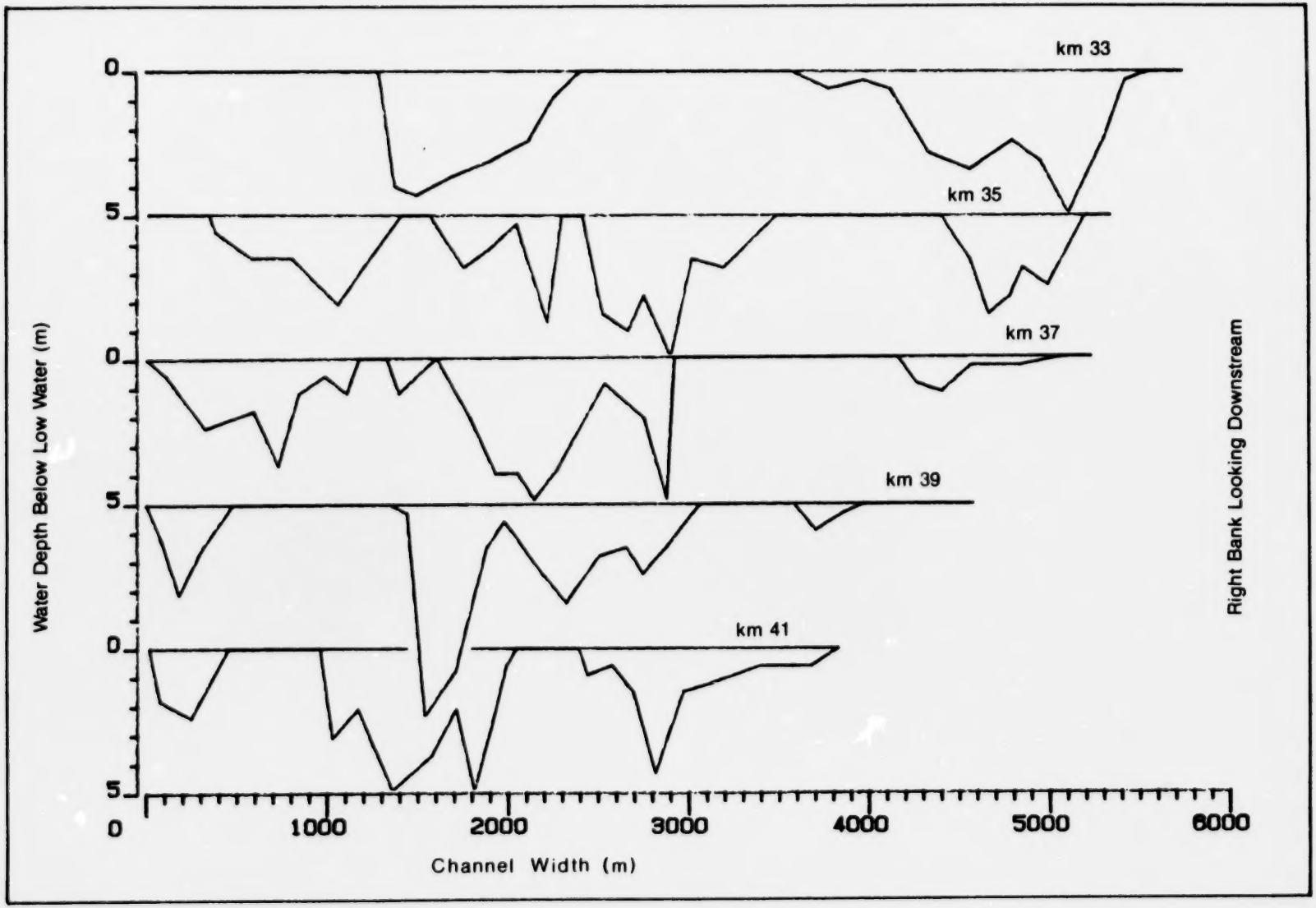


Figure 3.6: River cross-sections in the reach illustrated by Figures 3.3 and 3.4, digitized from the 1971 bathymetric field sheet. Vertical exaggeration 160x.

sheets. The comparison between them is a direct estimate of net vertical change in each measurement unit, provided we assume that the overall area of the unit has not changed appreciably. For a 7-year period in so large a river this is a reasonable assumption. Results are displayed in Table 4.1.

4.0 EVALUATION OF SEDIMENT TRANSFER IN A TEST REACH

4.1 REACH LOCATION AND CHARACTERISTICS

Mackenzie River is not entirely alluvial. Aside from such obvious bedrock control points as Sans Sault and the Ramparts, several substantial reaches are erosional in character. This reflects the degradational Holocene history of the river. Figure 4.1 gives a classification of alluvial sedimentary activity on a reach-by-reach basis, based on the presence of channel islands and adjacent flood plain. The classification approximately corresponds with a channel classification according to "braid index":

$$\text{Braid Index} = \frac{\text{total length of channel}}{\text{length of thalweg}}$$

For a braid index greater than 2.0 heavy alluvial sedimentation is supposed to occur. For a braid index between 1.0 and 2.0, moderate alluvial sedimentation is supposed to occur. Entirely single thread reaches are generally stable and non-alluvial. A planimetric map showing the location of the identified sedimentary units is presented as Table 4.2.

For a first test of morphological methods of estimating sediment transfer, a heavily alluvial reach is desirable, since erosion and deposition should be most active and most easily detected. After reviewing the available air photography, sediment data, and bathymetric charts (Appendix I), the 90 km section of river betweeen km 970 (downstream of Patricia Island) and km 880 (upstream of Ten Mile Island) was chosen as a test reach. The reach is characterized by sub-reaches of both heavy and moderate alluvial sedimentation. It has frequent air photo coverage and there are some sediment transport data available for Norman Wells. In addition, engineering investigations on the river here, in particular the 1979 report by Northwest Hydraulic Consultants, provide some additional information about the streambed.

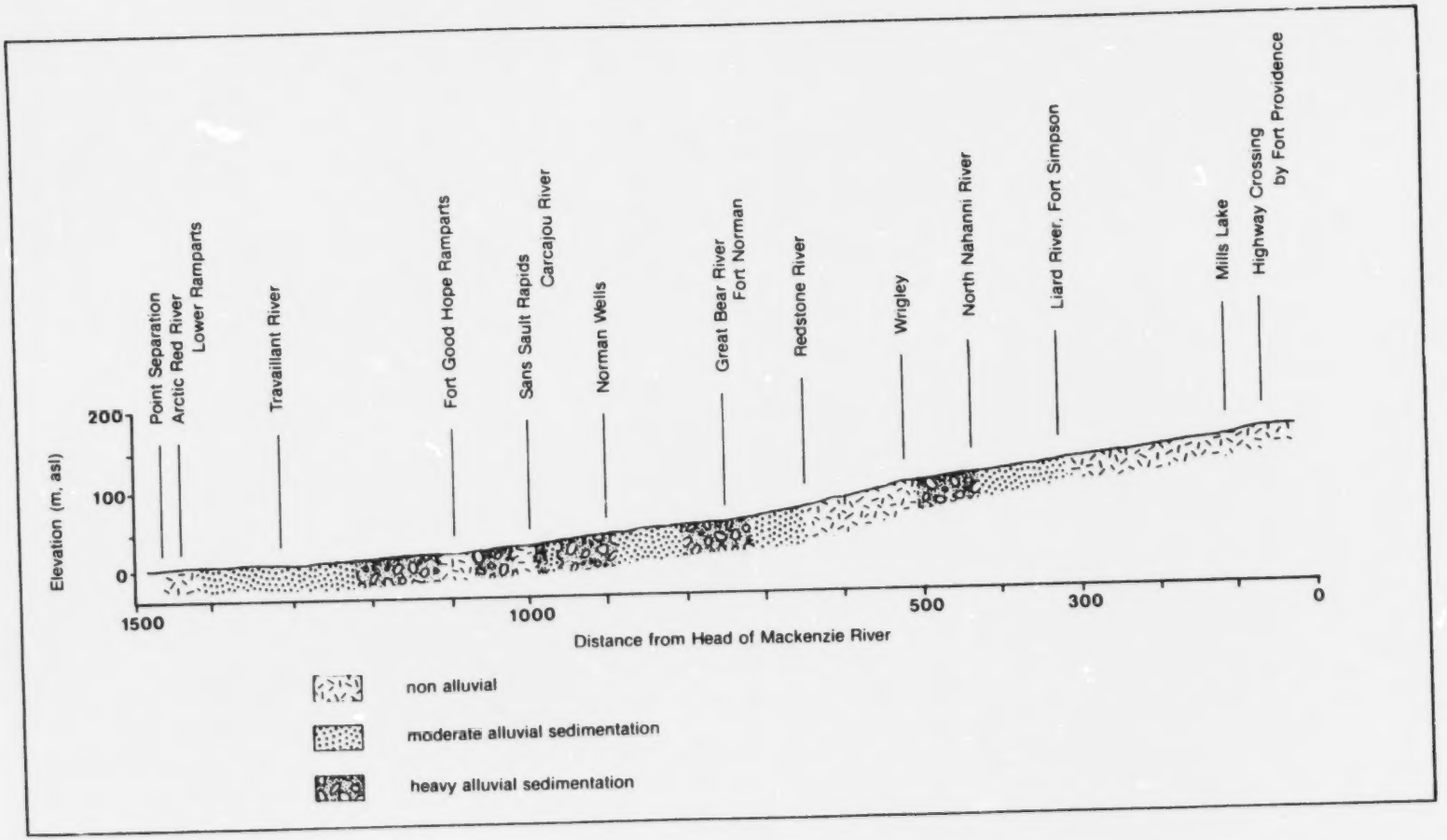


Figure 4.1: Long profile of Mackenzie River, showing areas of alluvial sedimentation.

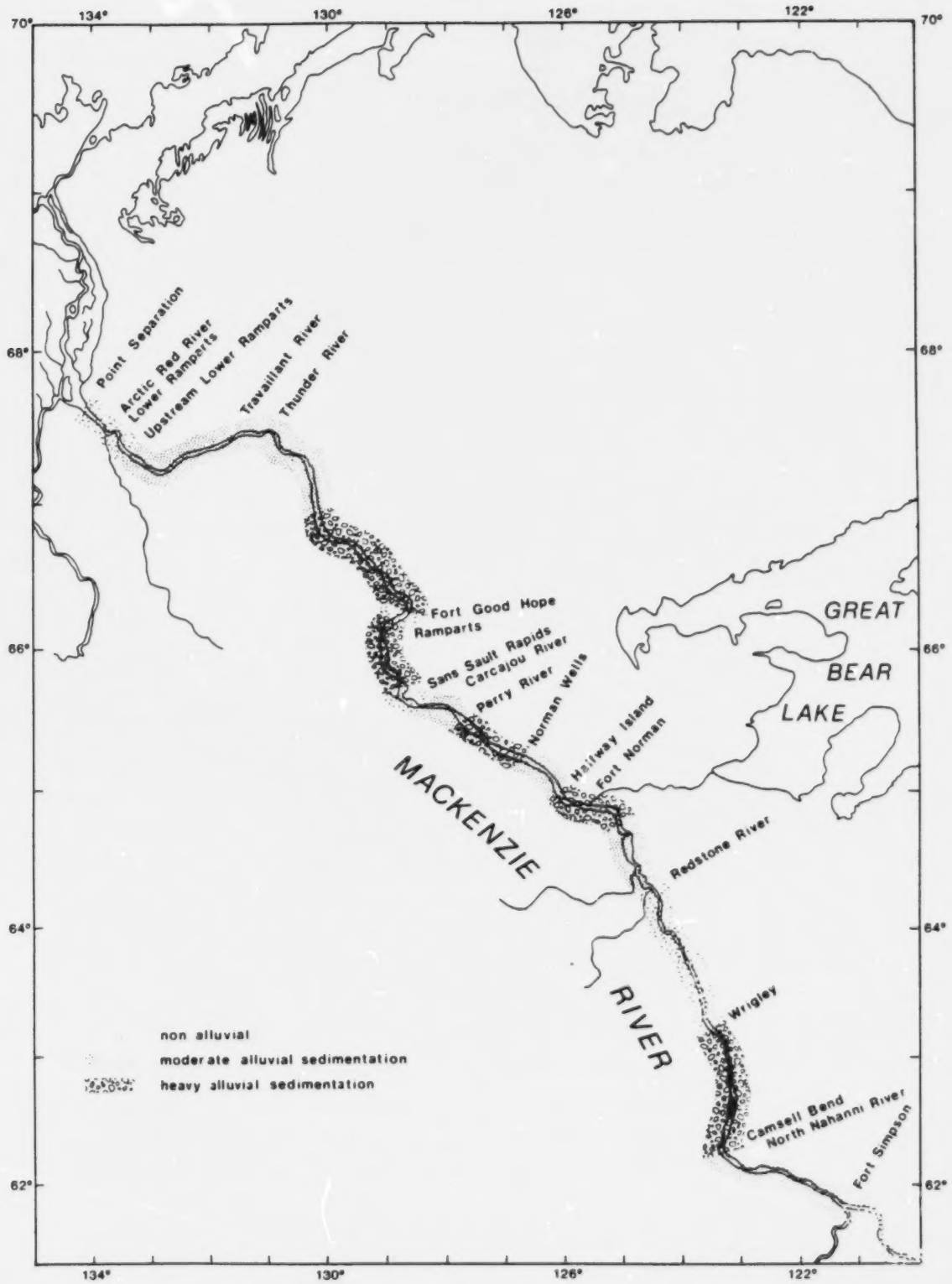


Figure 4.2: Planimetric map of Mackenzie River showing areas of alluvial sedimentation.

The streambed is not entirely alluvial in this reach. At Norman Wells, glaciolacustrine clay is exposed on the streambed (Hall, 1983). It has been preconsolidated to 10^3 kPa pressure, and is unlikely to be appreciably eroded under normal flows. This may be a helpful circumstance, since it allows the possibility for the height of alluvial bar structures in the river to be determined.

In addition, sandstone and shale are exposed in the right bank. Near Rader Island, diamicton - probably till - occurs in the channel bed. The alluvial bed is generally 1 to 4 m thick over these various subjacent materials (Northwest Hydraulic Consultants, 1979), which is scarcely greater than possible bedwave geometry at high flow.

Well-wooded islands in the reach represent a terrace, as do portions of the left bank which form a valley flat at the same level: they are higher than present flood levels. However, since high water in the reach is often induced by ice jams at the contracted sections near Ogilvie and Patricia Islands in the downstream portion, normal floodplain development on the lower islands and bars may be irregular, with frequent vegetation damage. The downstream portion of the reach, subject to ice jams and partly constrained by bedrock, contains less prominent alluvial deposits than the upstream portion. Figure 4.3 illustrates the test reach.

Rivers exhibit a more or less regular alternation of deep and shallow sections - termed pools and riffles - in channels smaller than Mackenzie River. The sequence is very well defined in meandered reaches, but may become quite obscure in ones with islands. Nonetheless, Figure 4.3 reveals an approximately regular sequence of 'riffle' through the channel islands and bars. There are 6 of them in the 88.7 km reach, for an average spacing of 14.8 km. The river has an average bank to bank surface width (including the islands) of 4280 m in the reach, so the 'riffle' spacing is 3.45 W_s. The repeating distance, or wavelength, is, then, 29.6 km on 6.90 W_s. The non-dimensional values fall remark-

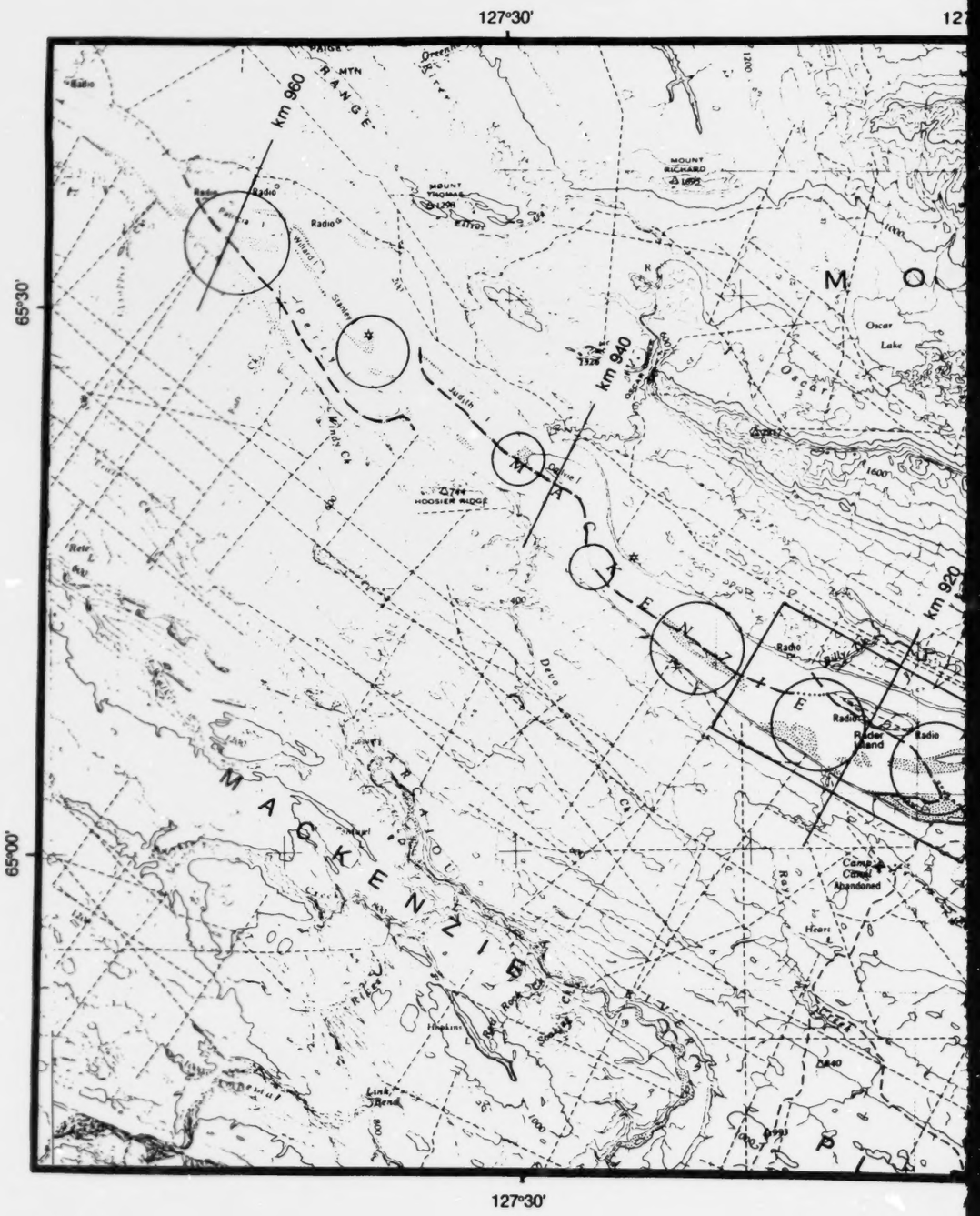
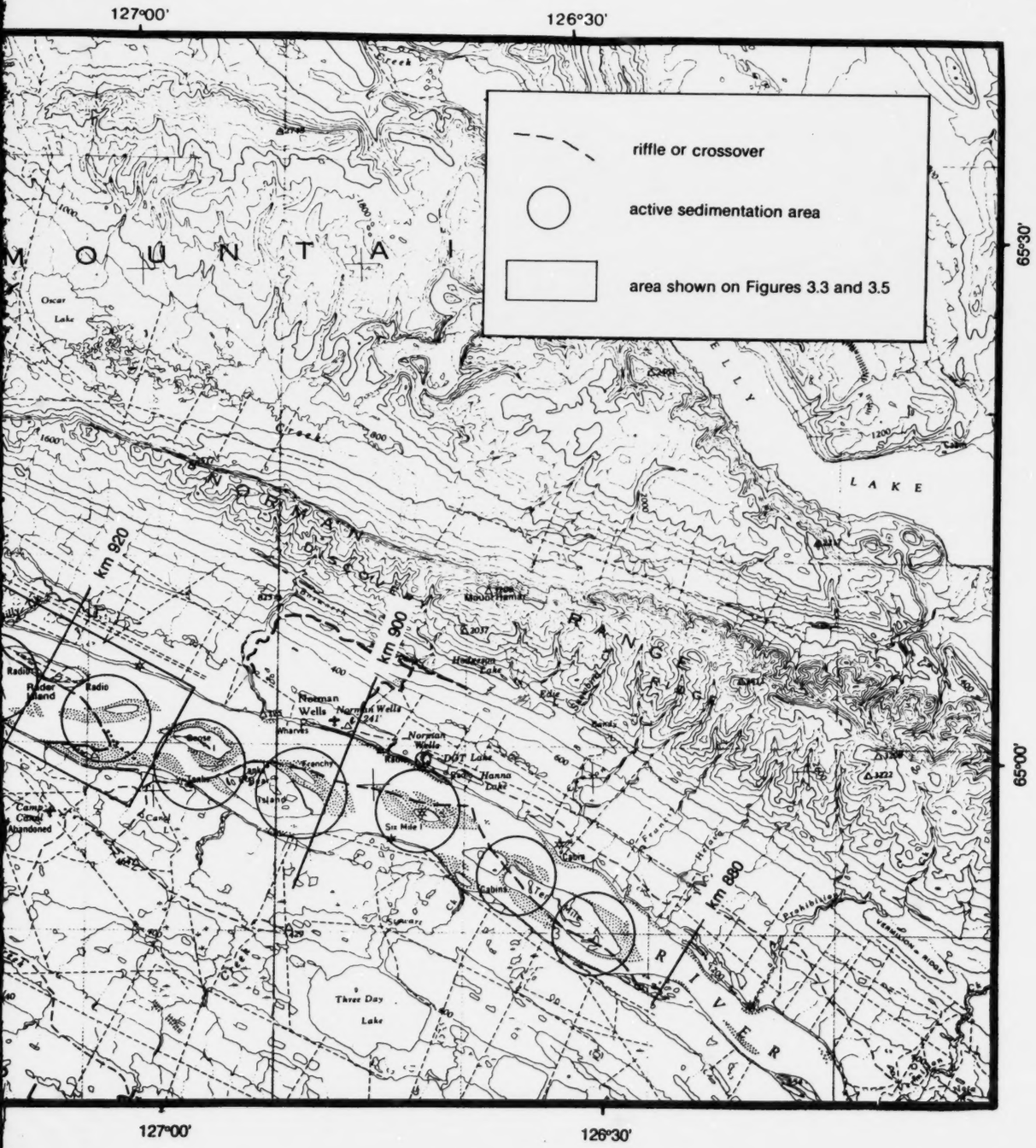


Figure 4.3: Test reach: km 887 to 968, showing the pattern of major pool and riffles (crossovers), and the major active sedimentation areas.



ably close to the rationally expected value (πW_s and $2\pi W_s$) for a river with no appreciably sinuosity. Associated with each riffle are two major zones of sand accumulation, usually at the head and tail of major islands perched on the riffle centre or anchored at one bend. The average spacing between these major sand accumulation zones is 7400 m. Either this figure or its double - the riffle spacing - is a candidate for bed sediment transfer distance in one event.

4.2 BATHYMETRIC CHANGES OVER THE PERIOD OF OBSERVATIONS

Summary data from soundings in the 36 km reach between the downstream end of Goose Island and the downstream end of Judith Island are presented in Table 4.1. The number of readings in each 2-km segment reflects the number of soundings presented on the field charts. Since the readings are not replicate measurements, the standard deviations should not be interpreted as a measure of statistical error, but as a descriptor of the variance of the depth.

On balance, there appears to have been net degradation between 1971 and 1978. The change was estimated by taking:

$$2000 \sum_i (X_{71i} - X_{78i}) W_i$$

where 2000 is the length of each segment, $\bar{X}_{71i}$ is the average channel depth in year 71, i is the segment location (in km) and W_i is the mean width of the segment at low water (obtained from the cross-sectional survey as the mean of the upstream and downstream limit sections for each segment). The number of observations was not used in the calculation. The 1978 survey was more intensive, but the general similarity of standard deviations suggests that the 1971 survey was adequate.

The result gives $\Delta S = -17.28 \times 10^6$ m^3 in the period 1971-1978. This represents -0.18 m bed level change or an 18 cm lowering on

TABLE 4.1: BATHYMETRIC DATA SUMMARY 1971 AND 1978

KM	1971 # OF READINGS	1971 AVERAGE DEPTH (m)	1971 STANDARD DEVIATION	1978 # OF READINGS	1978 AVERAGE DEPTH (m)	1978 STANDARD DEVIATION	REACH CONDITIONS IN 1978
29-31	52	2.24	2.10	147	2.62	2.18	one third area is sand bar
31-33	45	2.66	1.39	125	2.79	1.68	half area is sand
33-35	100	2.14	1.12	206	2.35	1.27	one third area is sand
35-37	56	2.09	1.48	185	2.16	1.53	half area is sand
37-39	70	2.14	1.34	175	2.10	1.50	approx. half area is sand
39-41	55	2.57	2.34	126	2.51	2.05	one half area is sand
41-43	99	1.90	1.18	178	2.04	1.20	one quarter area is sand
43-45	94	2.46	1.65	114	2.79	1.76	one third area is sand
45-47	50	2.54	1.43	98	2.47	1.39	approx. half area is sand
47-49	56	2.17	1.62	139	2.41	1.53	one quarter area is sand
49-51	71	2.29	2.00	132	2.75	2.28	one eighth area is sand
51-53	37	3.15	3.50	118	3.26	3.39	mostly water
53-55	42	4.09	3.69	100	3.93	3.63	one quarter area is sand
55-57	54	4.31	3.37	121	3.98	3.32	one half area is sand
57-59	48	3.68	2.88	119	3.80	2.93	one third area is sand
59-61	66	3.18	2.00	143	2.99	1.90	one third area is sand
61-63	84	2.33	2.17	118	3.60	2.56	one half area sand or island
63-65	64	2.45	1.99	157	3.03	2.43	one quarter area sand or island

average. The following constraints should however be noted in interpreting the result:

- it assumes that there is no bias in the reduction of data to datum in either survey;

- it applies only to the channel below normal low water: changes on the higher bar tops are not included;

- it does, however, include the effects of lateral channel shifting by scour and fill;

- the figure is net for the period, hence it is a lower bound estimate for sediment transport;

- the figure probably encompasses a high proportion of net change in bed material (which will not be lifted onto bar tops).

The calculated result represents about 2.45×10^6 m^3 deflation per year of material, 54 per cent of which was removed from the two most downstream segments (km 61-65) around Judith Island.

As a rough indication of the precision of the result, the standard deviation is 2.5 and number of samples is ≥ 50 in each segment, so the precision of a difference is on the order of $\pm$ 0.5 units, hence the pooled mean for the 18 segments (ignoring width fluctuations) would be of order $0.5/(18)^{0.5}$ or approximately $\pm$ 0.1 m. This yields a precision estimate which is about the same as the indicated degradation. The true value might vary between 0 and twice the calculated totals (again, assuming no bias in either data set).

The foregoing calculations are relatively convenient and could be made more precise with additional data from automated soundings. The conduct of river surveys at relatively high flows and reduction to a higher datum would permit more of the channel zone

to be included in the calculations as well. The calculation would however represent only a net estimate of change in material volume.

4.3 PLANIMETRIC CHANGES IN THE PERIOD OF AIR PHOTO RECORD

Apparent changes in the periods 1950-1962 and 1961-1971 were assessed by digital planimeter from maps like that illustrated in Figure 3.3c. Data were compiled by 2-km segment, but these were then summarized into reaches according to the change in water level between the two maps. The reach limits were set by the photographs used in the compilaton, the dates of which determined the observed stages. Results are reported in Table 4.2.

The effect of stage changes is apparent in the data, especially as displayed in Figure 4.4, where abrupt changes in $\Delta A = A_d - A_e$ correspond with photo coverage limits. From the stage data of Table 3.2, stage difference, Δz, can be estimated between the maps obtained for two successive dates. These are also reported in Table 4.2. A major difficulty arises in that the stage on August 20, 1962 is unknown. Photography downstream from km 24 (Bear Island) was all flown on this date for this map, which is involved in both comparisons. Figure 4.5 shows plots of daily stage data kept during the late summer of 1962 at Fort Norman (upstream) and Sans Sault (downstream) respectively, and some isolated levels that are available at Norman Wells. On August 20, Norman Wells stage almost certainly fell within the range 49.0-49.4, that is 20.0-20.4 ft Norman Wells datum. The air photos imply that the stage was considerably above the 1950 level; so we accept 20.4 ft or 6.2 m as an approximate 1962 datum.

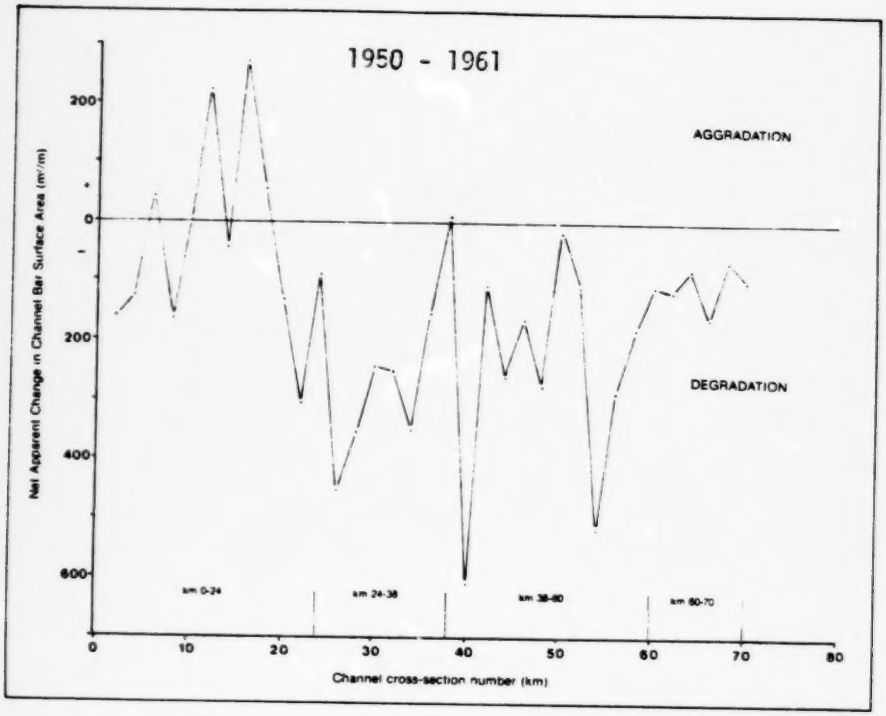
On the basis of the known or assumed stage changes, then, corrected values of A_e and A_d are computed and presented in Table 4.2. For purposes of the computations, dw/dz was taken to be 0.025, the value assumed for stages in the range +4.0 to +6.0 m (Norman Wells stage datum) from the average hypsometric curve of the entire reach (Figure 4.6).

TABLE 4.2: SUMMARY OF OBSERVED PLANIMETRIC CHANGES AND ESTIMATED ADJUSTMENTS

REACH	Ad	Ae	$\bar{W}c$	L	Z *1		$Lr.\bar{W}c \frac{dw}{dZ} Z$	Adc	Aec	A	YEARS OF RECORD
(km)	(m x 10)	(m x 10)	(m)	(m x 10)	(m)		(m x 10)	(m x 10)	(m x 10)	(m x 10)	
					1950-1962						
0-24	3143	4000	3333	24	+0.6		1200	4343	2800	+1543	11
24-38	933	4579	3787	14	+2.2	*	2916	3849	1663	+2186	12
38-60	137	5484	2898	22	+0.4	*	637	774	4847	-4073	12
60-70	324	1382	3232	10	+0.9	*	728	1052	654	+398	11
24-60								4623	6510	-1887	12
TOTAL								10018	9964	+54	
					1961-1971						
0-12	574	3444	2888	12	+1.0		866	1440	2578	-1138	10
12-24	526	2495	3777	12	+0.6		680	1206	1815	-609	10
24-30	2775	276	3203	6	-1.1	*	-528	2247	804	+1443	9
30-50	4434	900	3752	20	-0.9	*	-1688	2746	2586	+160	9
50-76	7344	426	3100	26	-1.5	*	-3023	4321	3449	+872	9
0-24								2646	4393	-1747	10
24-76								9314	6839	+2475	9
TOTAL								11960	11232	+728	

*1 Asterisked values are based on an assumed 1962 stage (see text). Z from km 38 downstream is adjusted by a factor 1.33 x over the indicated change at Norman Wells, in accordance with the stage correlation printed on Hydrograhic Chart 6419. In the second decade, the adjustment is applied from km 30 on.

$$Adc = Ad + Lr.\bar{W}c \frac{dw}{dZ} Z; \quad Aec = Ae - Lr.\bar{W}c \frac{dw}{dZ} Z; \quad \frac{dw}{dZ} = 0.025$$



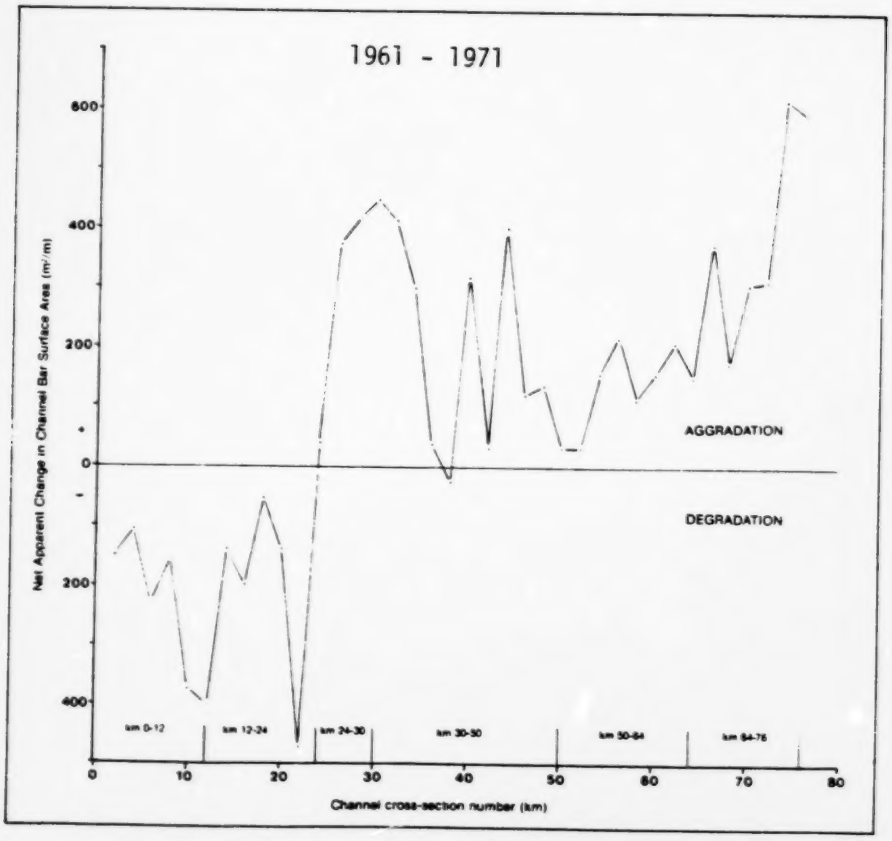
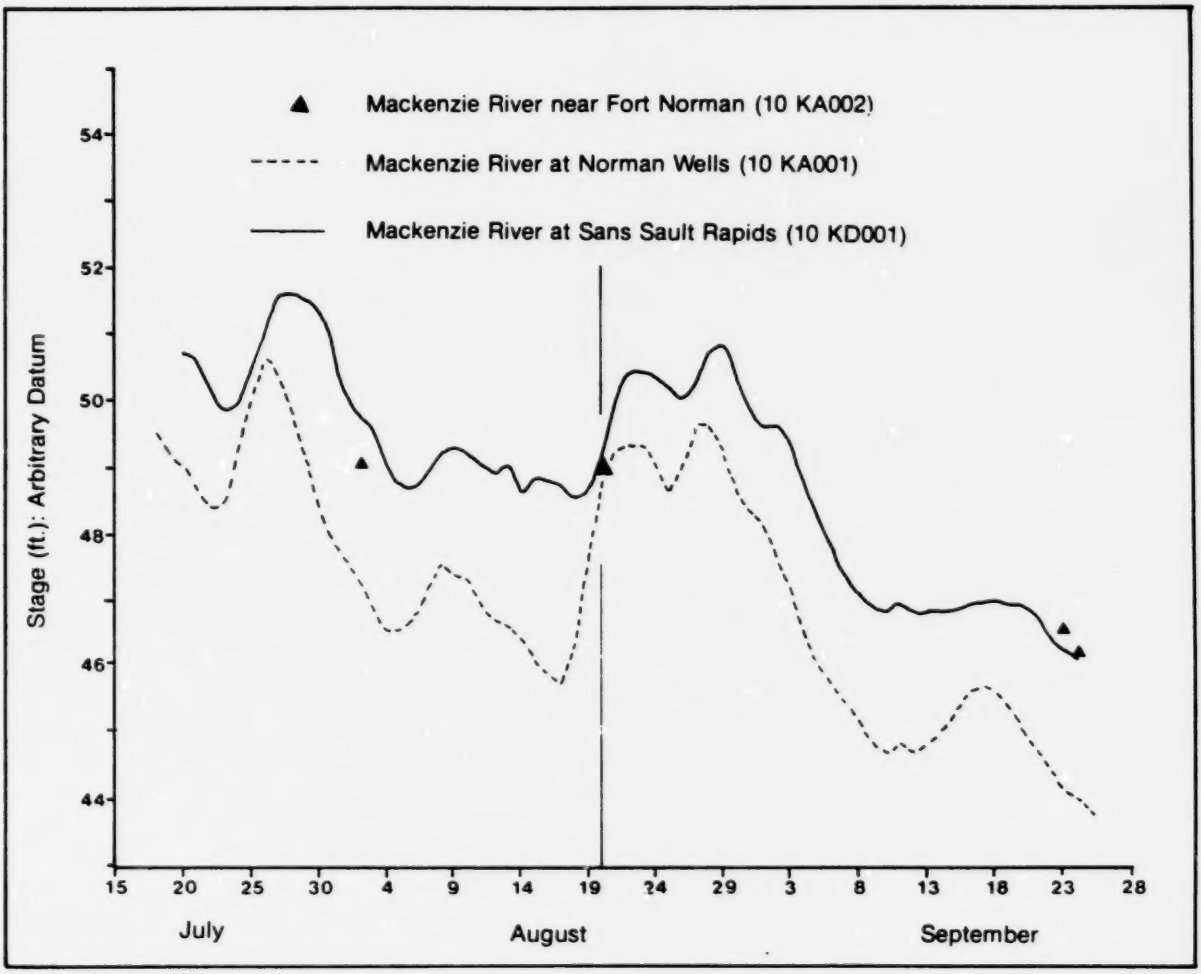


Figure 4.4: Net apparent change in channel bar surface area expressed as m^2/m length, or apparent change in channel width



Note: - subtract 29.0 ft. to obtain Norman Wells datum;
- add 9.0 ft. to obtain San Sault datum.

Figure 4.5: Stage records during July to September, 1962 for stations near the test reach. A reasonable range, within which the Norman Wells datum almost certainly falls, is shown for August 20.

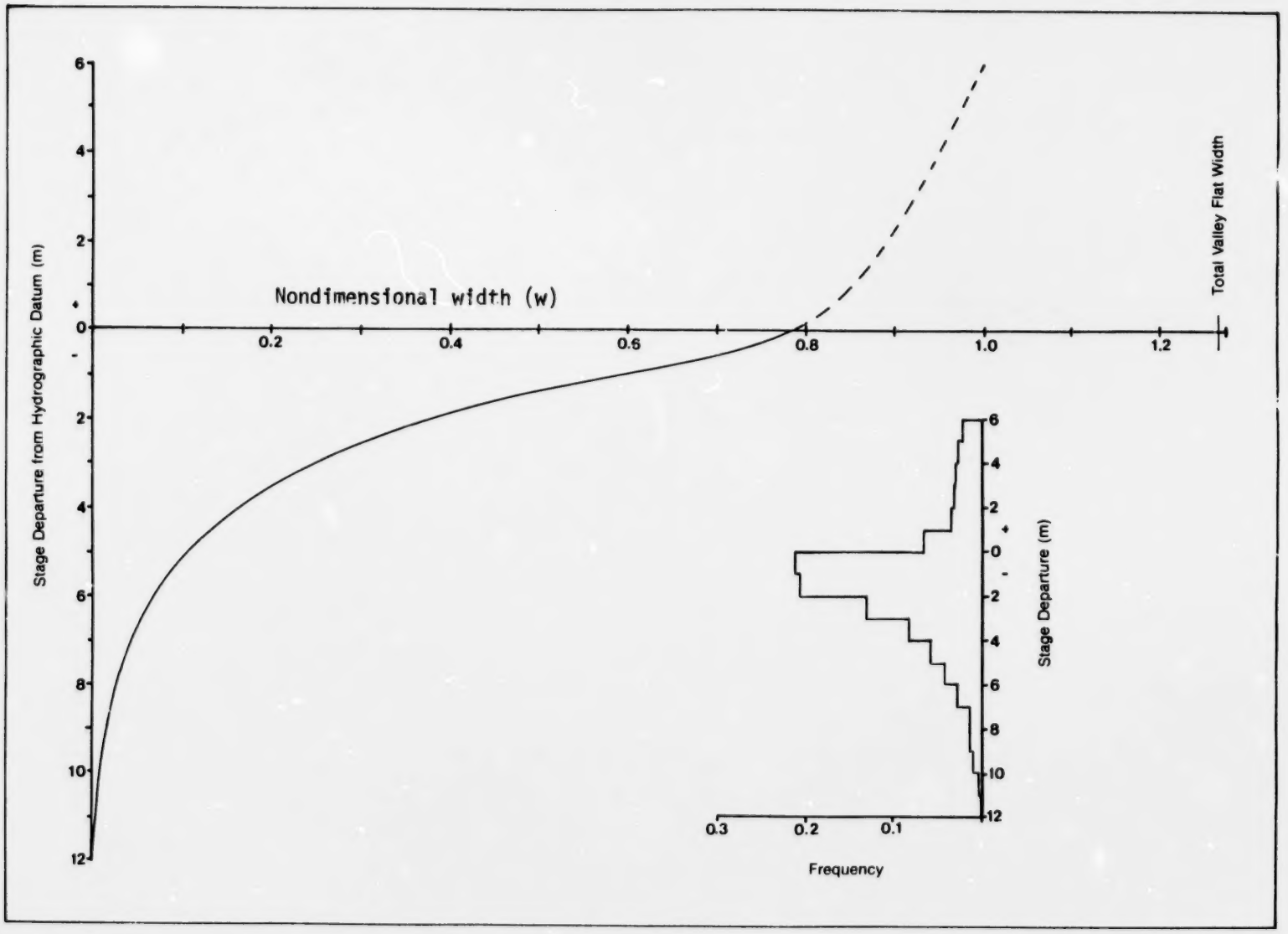


Figure 4.6: Hypsometric curve of the test reach and distribution of depth. Above stage 0.0 (Norman Wells datum) the hypsometric curve is extrapolated so that the flow width will equal full channel width at +6.0 m.

It is difficult to comment on the precision of these computations. Accuracy can be considered by examining the consistency of the results. Over the 70+ km reach, erosion and deposition of bed material should very nearly balance over a period of a decade (though not necessarily over a shorter distance within the reach, of order one or two pool/crossover lengths), and this should be reflected in the planimetric changes. Table 4.2 presents $\Delta A = A_{dc} - A_{ec}$. For the period 1950-1962, the net change over the entire reach is +54,000 m^2, which is about 0.5 per cent of the 10 x 10^6 m^2 magnitude of A_d and A_e. In 1961-1971, the net change is +728,000 m^2, which is about 6 per cent of turnover. These results are very reasonable.

It is interesting to note that, in the upstream 24 km reach (for which actual stage observations are available on all dates and which contains the gauge), the 20-year balance is as follows:

1950-1961:	+ 1,543,000 m^2
1961-1971:	- 1,747,000 m^2
	- 204,000 m^2

The change is about 12 per cent of turnover, and is not unreasonable for a reach of 2 pool/crossover units length.

The results arrived at in this section should be compared also with the result from bathymetric soundings (Section 4.2) of 2.45 x 10^6 m^3/yr net loss from the reach km 29-65 during 1971-1978. If we suppose that material was mainly stored as 6 m deep sand banks (the assumption in this section), then 11.4 m^2/yr/m length were lost. For comparison, the reach km 24-60 lost 4.4 m^2/yr/m net 1950-1962, and km 24-76 gained 5.3 m^2/yr/m net in 1962-1971 (2.5 m^2/yr in km 30-76). The figures based on the bathymetry seem to be somewhat high, even granted that larger floods occurred during the 1970's than during the preceding 20 years. There may, then, be some bias in the bathymetric comparison.

4.4 CHANGES IN SEDIMENT STORAGE IN THE PERIOD OF RECORD

Results from the last section can be expressed as bed sediment transfer if estimates are available of the depth of mobile material and of the characteristic transfer distance.

Figure 4.6 includes a histogram of distribution of depth, derived from the hypsometric curve, which shows that most of the channel bottom falls between +1.0 m and -7 m. There is no obvious break on the lower side, however, Figure 4.7 presents a histogram of the maximum depths observed in the 38 measured cross-sections. There is an obvious modal class at 5-6 m depth. For purposes of sediment transfer calculations we have therefore assumed that the mobile sand banks are typically 6 m thick, that is, extending between +1.0 m and -5.0 m.

Candidate step lengths are 7400 m (bar complex or sedimentation zone distance) or 14,800 m (crossover distance).

Table 4.3 presents results which are weighted for the actual period between successive photographs in each portion of the reach. These results indicate bed sediment transport rates ranging from 542,000 to 759,000 m^3/yr. Assuming a bulk density of 1.8 tonnes/m^3, these values are equivalent to 997,000 to 1,366,000 tonnes/yr. The high result is based on the relatively large aggradation in the downstream portion of the reach in the 1962-1971 period and probably should be disregarded. The remaining values all indicate similar annual bed sediment transfer rates of 1.0×10^6 tonnes/yr. In a local calculation we should prefer the results based upon S_e as indicating local transport capability, but over 70 km it should make little difference which component is used, so long as the estimates are regarded as unbiased.

We may further assess the indicated bed material transport of 1.0×10^6 tonnes/yr by comparison with the total suspended sediment transport as measured at Arctic Red River. The 11-year average there for the period 1974-1983 is 88.2×10^6 tonnes/yr

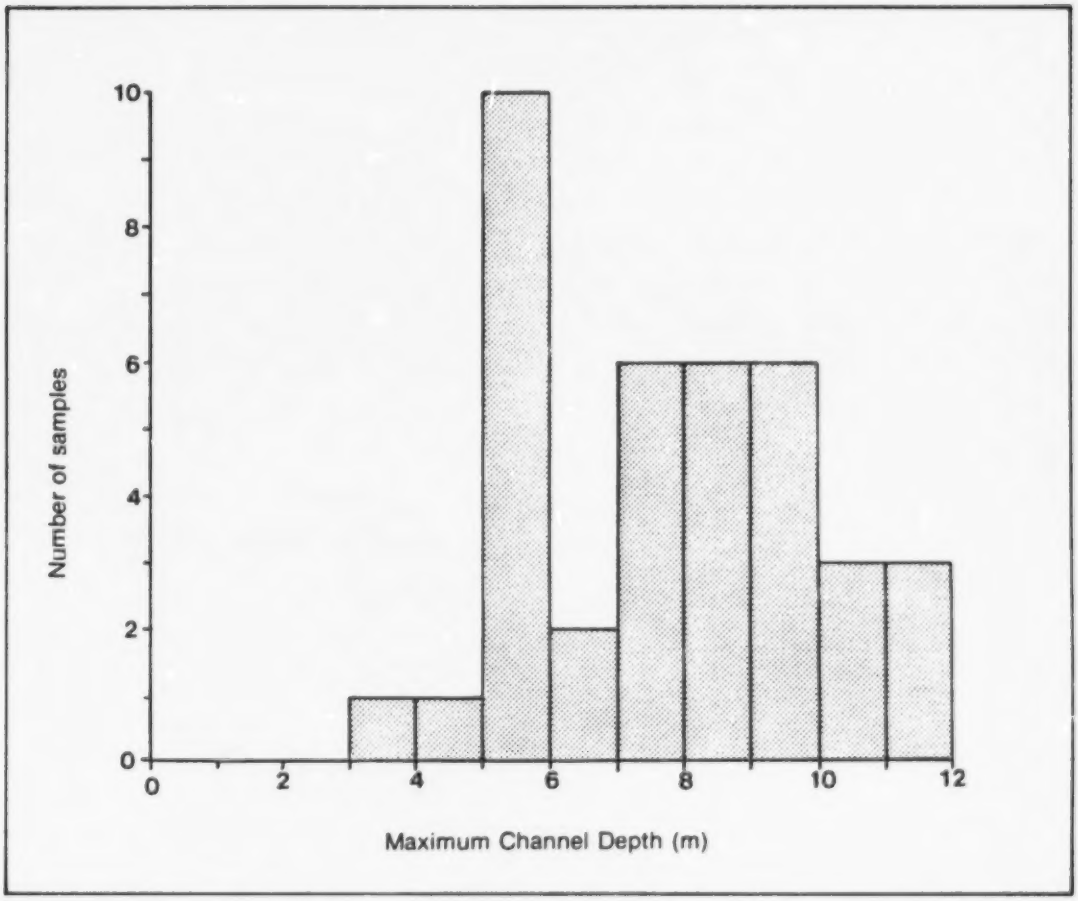


Figure 4.7: Histogram of maximum channel depth, n = 38.

TABLE 4.3: ESTIMATE OF BED SEDIMENT TRANSFER IN THE TEST REACH (Lt = 7400 m)

PERIOD	ANNUAL BANKLINE CHANGE (m) BASED ON: ×1		REACH LENGTH (Lr) (m)	ANNUAL BED SEDIMENT TRANSFER (Sb) (m3/year) ×2		ANNUAL BED SEDIMENT TRANSFER (tonnes/year) ×3	
	Sd	Se		From Sd	From Se	From Sd	From Se
1950-1962	12.5	12.2	70,000	555,000	542,000	990,000	975,000
1961-1971	(17.1)	13.4	76,000	(759,000)	595,000	(1,366,000)	1,071,000

×1 Equals Adc or Aec (Table 4.2) divided by reach length (Lr) and the number of years between planimetric mapping ("years of record", Table 4.2).

×2 Equals annual bankline change × mobile sediment depth (assumed to be 6 m) × sediment travel distance (Lt).

×3 Bulk density of sediment assumed to be 1.8 tonnes/m3.

(C.P. Lewis, personal communication, 1986), and there is only a small overlap between grain size ranges of suspended material at Arctic Red River and bed material in the river. The ratio between the two figures is 0.011, and it is probable that the bed material transport comprises a somewhat larger proportion of the total load - say of order 1.5 per cent. This is a reasonably expected figure, perhaps a bit on the low side, for a sand bed river. [1]

The foregoing calculations assume that L_t = 7400 m. If it were 14,800 m (pool-crossover spacing), then the transport estimates would be doubled. At 3 per cent of total load, this would still be reasonable, but in the upper part of the expected range. The 2 x uncertainty represented in this spread is about the same as would be derived from some years' of measurements of bed material transport, and should not be regarded as excessive.

In fact, material probably exhibits a spectrum of travel lengths, once entrained. Granules may move only a few hundred metres along a bar face; fine sand may very well travel in intermittent suspension in a season right through a pool reach. A correlation of grain size and transport length would produce figures for transport between 1 and 2 million tonnes/yr, probably closer to the upper figure. We lack data to pursue this question further.

---

1. Northwest Hydraulics Consultants obtained an estimate for bed material transport of 0.3×10^6 m^3/yr using similar methods, but based on only casual measurement at Norman Wells. The result is converted to 0.75×10^6 tonnes/yr, which assumes a bulk density of 2.5, which is too high. A more realistic conversion would yield 0.5×10^6 tonnes/yr, just one-half our estimate and probably too low. Restricting our attention to the upstream 24-km subreach, which includes the Norman Wells area, we obtain, over the full 21-year record, consistent transport estimates of 1.11×10^6 tonnes/yr and 1.14×10^6 tonnes/yr, the larger based on S_e, that is about 10 per cent larger than our reach-averaged estimate, and still twice the Northwest Hydraulics Consultants figure.

These estimates, of course, remain lower bounds because erosion and deposition may occur at a site on a seasonal basis or within a few years. We expect, then, that the true result is toward 2 million tonnes.

4.5 CHANGES IN ALLUVIAL HABITAT IN THE PERIOD OF RECORD

The exercise described in Section 4.3 was repeated for the changes in vegetated area on banks and islands by planimetering areal changes indicated by changing vegetation limits. In this case, no adjustments are made for stage change. There remains some possibility of bias on the side of excessive loss of habitat if low cover - such as grasses - is submerged at high stage (particularly as photographed downstream from km 24 in 1962).

The results of this analysis are shown on Table 4.4 From 1950 to 1962, gain in alluvial habitat was nearly double the loss over the entire reach. In the second decade, gain out-stripped loss by about 20 per cent, and the overall gain was only half that in the previous period. In 1951-62, gain in covered area actually exceeded gross deposition area (Compare Table 4.4 with Table 4.2).

There are variations along the river, which are best revealed in the last two columns of Table 4.4, which give changes per unit river length (effectively advance and retreat of the vegetation limit on a cross profile). The figures are generally within the range of 5 to 10 m/yr, except for 22.2 m/yr progradation in the upstream reach in the first period and 10.6 m/yr retreat there in the second decade. These rather large figures correspond with notable net change in sediment stored in this reach between the two decades. Only in the reach 24-60 km in the first decade was the balance of change in the opposite sense to that of sediment changes.

The remarkable gain in habitat in the 1951-62 period possibly reflects the comparitively small annual maximum daily discharges

TABLE 4.4: CHANGE IN ALLUVIAL HABITAT

REACH (km)	Ad ($m^2 \times 10^3$)	Ae ($m^2 \times 10^3$)	n (yrs)	$\bar{A}d$ ($m^2 \times 10^3/yr$)	$\bar{A}e$ ($m^2 \times 10^3/yr$)	$\bar{a}d$ ($m^2/yr/m$)	$\bar{a}e$ ($m^2/yr/m$)
			1950-1962				
0-24	5871	2174	11	534	198	22.2	8.3
24-60	4536	3096	12	378	258	10.5	7.2
60-70	895	588	11	81	53	8.1	5.3
TOTAL	11302	5859					
			1961-1971				
0-24	1367	2547	10	137	255	5.7	10.6
24-76	4640	2530	9	516	281	9.9	5.4
TOTAL	6007	5077					

where: Ad = area of sediment deposited
Ae = area of sediment eroded
n = number of samples
$\bar{A}d$ = average area of sediment deposited per year
$\bar{A}e$ = average area of sediment eroded per year
$\bar{a}d$ = average area of sediment deposited per metre of channel length per year
$\bar{a}e$ = average area of sediment eroded per metre of channel length per year

which occurred in the period 1943-1963. Table 4.5 shows the historical variation in annual maximum daily flows recorded at the gauging station Mackenzie River at Norman Wells and their respective return periods (estimated using the Pearson Type III distribution fitted by the method of moments). These data and the graph of annual maximum daily flows recorded over the period of record (Figure 4.8) indicates an apparent trend of increasing flood discharges. The average annual maximum daily flow in the period 1943-1962 is 19580 m^3/s. The post-1962 average is 24,080 m^3/s or a 23 per cent increase in average value. A variety of tests can be employed to determine if this apparent trend is statistically significant. Q, R and W statistics (described in Buishand, 1982) indicate there is a 95 to 99 per cent probability of a change in peak flow regime at Norman Wells.

TABLE 4.5: ANNUAL MAXIMUM DAILY FLOWS AND RETURN PERIODS, MACKENZIE RIVER AT NORMAN WELLS

YEAR	ANNUAL MAXIMUM DAILY FLOW (m3/s)	RETURN PERIOD (yrs)	AVERAGE VALUE - DECADE: ANNUAL MAXIMUM DAILY FLOW (m3/s)	AVERAGE VALUE - DECADE: RETURN PERIOD (yrs)	YEAR	ANNUAL MAXIMUM DAILY FLOW (m3/s)	RETURN PERIOD (yrs)	AVERAGE VALUE - DECADE: ANNUAL MAXIMUM DAILY FLOW (m3/s)	AVERAGE VALUE - DECADE: RETURN PERIOD (yrs)
1940	-				1970	20,600	1.4		
1941	-				1971	21,500	1.6		
1942	-				1972	25,500	4.2		
1943	17,600	1.13			1973	24,800	3.4		
1944	17,900	1.14			1974	27,500	9.0		
1945	14,200	1.02	19,560	1.3	1975	30,300	40.0	24,950	3.6
1946	-				1976	22,000	1.8		
1947	24,700	3.3			1977	28,300	13.0		
1948	-				1978	24,100	2.8		
1949	23,400	2.3			1979	24,900	3.5		
1950	18,000	1.15			1980	-			
1951	18,200	1.16			1981	-			
1952	21,900	1.7			1982	26,900	7.0	24,975	3.6
1953	16,600	1.08			1983	25,000	3.6		
1954	-				1984	19,800	1.3		
1955	23,300	2.3	19,600	1.3	1985	28,200	13.0		
1956	-								
1957	-								
1958	-								
1959	-								
1960	-								
1961	-								
1962	-								
1963	27,200	8.0							
1964	-								
1965	19,300	1.3	22,033	1.8					
1966	20,800	1.5							
1967	22,500	1.9							
1968	25,000	3.6							
1969	17,400	1.11							

Note: Return periods were estimated using the Pearson Type III distribution fitted by the method of moments.

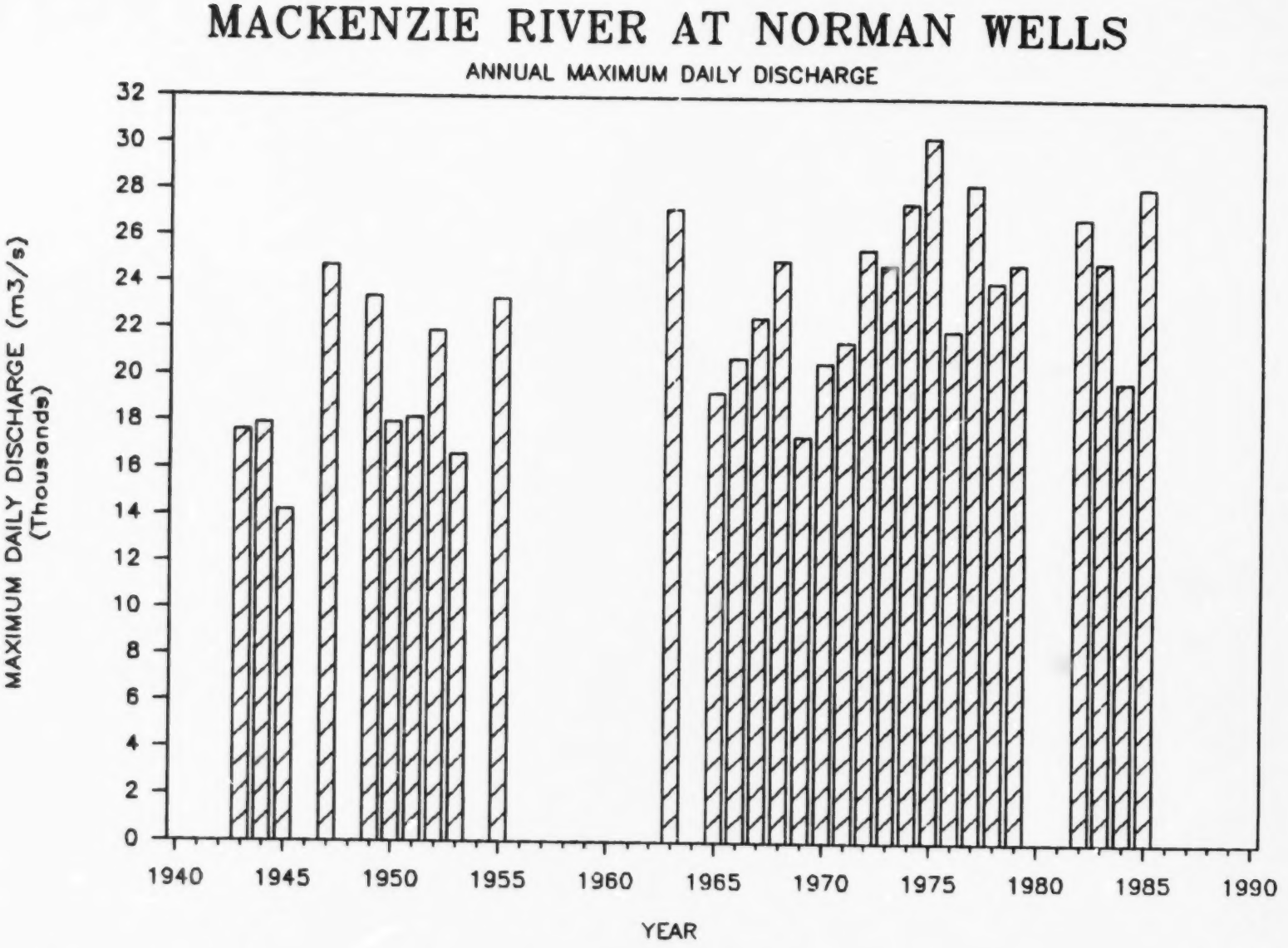


Figure 4.8: Historical variation in annual maximum daily discharge, Mackenzie River at Norman Wells.

5.0 PROJECT ASSESSMENT

5.1 FEASIBILITY OF SEDIMENT TRANSFER EVALUATION

There is no straightforward means by which to verify the results arrived at in Section 4. However, their consistency suggests that they are reasonable. Superficially, then, this method for estimating rates of bed material transfer along the river appears to be feasible. The range of uncertainty in the calculations is no greater than is obtained after some years of conventional measurements. There remains the possibility that the results are negatively biased, but conventional measurements have similarly been subject to bias because of inadequate understanding of sampling and analysis procedures (cf. Church et al, 1985, Appendix 1; McLean and Tassone, in press). Finally, bed material moving as bed load is very difficult to measure directly in any case. The technique based on morpholoIgical changes is, therefore, attractive.

There are some features of the test reach that were advantageous in this preliminary study:

(i) there is a gauge in the reach;

(ii) there is some information available about bed materials;

(iii) the pool-crossover sequence and sedimentation zones are relatively clearly defined; and

(iv) there are substantial bed material deposits visible through most of the reach.

Other reaches of the river where these conditions are not so favourable may be more difficult to assess. On the other hand, it is not necessary to make estimates continuously along the river. Alluvial reaches, similar to the test reach, and adjacent to

gauges would be best. Table 5.1 gives a suggested list of reaches for definitive study. The priority ranking is based upon our judgement of the likely resolution in the results, and the projected practical significance of the information. The list includes all of the reaches with extensive alluvial habitat. Test reach length is set by the requirement to average estimates over several pool-crossover units: 5 to 10 units are desirable, setting reach lengths of approximately 75 to 100 km (the length scale may be smaller near Liard River than it is in the vicinity of Norman Wells).

5.2 FEASIBILITY OF TOTAL SEDIMENT TRANSPORT EVALUATION

As was noted in Section 1.2, total sediment transport evaluation must begin from a station where wash load (in this river, comprising the majority of the suspended sediment) is measured. The only substantial records are at Stations 10LA003 (Mackenzie River above Arctic Red River) and 10ED002 (Liard River near the Mouth)(Figure 2.1). These stations conveniently bracket the main stem of the river and are adjacent to reaches recommended for study (Table 5.1).

Provided that reasonable information were available on bed material size, it should be possible to extend computations upstream from Arctic Red River to Sans Sault - where Mountain River enters. Downstream calculations from Fort Simpson would be limited at Camsell Bend, where North Nahanni River enters. Establishement of a suspended sediment rating curve at Norman Wells may allow calculations to be extended along the entire river (subject, of course, to satisfactory error control), and a valuable check could be gained if Keele River were rated.

TABLE 5.1: MACKENZIE RIVER REACHES SUITABLE FOR MORPHOLOGICAL ESTIMATES OF SEDIMENT TRANSFER

REACH [1]	RIVER KILOMETRE	LENGTH (km)	GAUGE	REMARKS	PRIORITY
Ft. Simpson (Liard confluence) - Camsell Bend (N. Nahanni R.)	333-451	118	M.R. at Fort Simpson	moderately alluvial: may be few changes d/s Fort Simpson	2
Camsell Bend - Wrigley	451-563	112	M.R. near Wrigley	heavily alluvial: major load delivered by N. Nahanni R.	5
Redstone R. - Ft. Norman (Gt. Bear confluence)	715-821	106	M.R. near Ft. Norman	Keele R. load added	7
Halfway Island - Perry Island	852-965	113	M.R. at Norman Wells	includes test reach	3
Sans Sault Rapids - Ramparts	1015-1086	71	M.R. at Sans Sault Rapids	Mountain R. load added	4
Fort Good Hope - Thunder River	1095-1295	200	M.R. at Fort Good Hope	possibly two reaches: d/s one centred on Little Chicago	6
Thunder R. - Lower Ramparts (u/s Arctic Red River	1295-1425	130	M.R. above Arctic Red River	estimates sediment yield to delta	1

Notes: 1. Reach locations are shown on Figure 4.2

M.R. stands for Mackenzie River;
d/s stands for downstream

5.3 INFORMATION REQUIREMENTS

Information can be considered under headings of special requirements and continuing surveys. A division also may be made between field activities and non-field activities required to collect the information.

5.3.1. Special requirements, field:

One of the main constraints in this report is the necessity to adopt an averaged cross-sectional profile of entirely conjectural form above 'low water'. A sequence of cross-sections through the selected study reaches, carried to bank top, would be necessary in definitive computations to permit stage adjustments to be made for changes mapped from air photography. The 2-km spacing adopted in this report would be convenient but onerous. For a 75 km reach, there are 38 sections. For computations, results should be averaged over 15-km units, with breaks being established particularly at places where the style of sedimentation changes. This is an onerous requirement: the work could be substantially reduced if soundings taken near high water were available. It may be possible to complete the definition of bank lines by photogrammetry from 1:20,000 photography where it is available. The river, of course, changes the form of its section as a result of sediment transport. However, the averaged results should remain valid for some decades as a description of the hypsometry, unless persistent aggradation or degradation occurs within a reach. It may be possible to avoid this requirement for future assessments (but not retrospective ones) if bathymetric surveys are undertaken at high water (see below, Section 5.4.2).

Bed material composition in the measurement reaches, and more generally along the river, must be known in order to determine:

i) the size of material moving as bed load; and

ii) the distribution of alluvial materials in the reach.

Most of these measurements can be made in the field and only a restricted subset of samples need be recovered for detailed texture analysis.

Photographic documentation of sand bar surfaces, vegetation edges and riparian vegetation in the test reaches could be an aid to the photogrammetrist for construction of maps of waterline and vegetation trim line positions.

5.3.2. Continuing requirements, field:

There have been remarkable advances, in recent years, in navigation techniques and data storage systems for sonar surveys. The periodic hydrographic surveys of the river could fulfill most of the requirements for bed material transfer assessment if the field information were available in appropriate form. This would be very inexpensive to arrange if the data were initially digitally recorded with navigation coordinates. For example, Terra Surveys Ltd. of Sidney, B.C. conducted bathymetric surveys on Mackenzie River for the Canadian Hydrographic Service during the summer of 1986. The surveyed area extends between km 0 (Great Slave Lake) and km 208 (20 km downstream of Mills Lake). Discussions with Mr. F.J. Quinn, P.Eng. of Terra Surveys indicate the navigation precision of their surveys is $\pm$ 5 to 10 m, water depths are precise to $\pm$ 30 cm, cross-sections are located at 200 to 250 m intervals and most of the surveys were conducted during high water conditions. All of these data are stored digitally. This information is substantially more precise than that which was available for the present study and, once repetitive surveys are available and the appropriate computer software written, these data would allow changes in bathymetry to be determined on a routine, cost-efficient, basis.

Our retrospective examination of the early bathymetric surveys revealed several difficulties in using old information. The data are available on 'field sheets' reduced to low water datum. The actual survey data may well have included soundings over bar tops,

which could have reduced the range of conjectural extension of the hypsometric curve. The Canadian Hydrographic Service was reluctant to release even the reduced soundings to us for policy reasons: the Service wishes not to release obsolescent data which might then be used for attempted navigation or planning purposes. We expect that this matter can be avoided in the future if the Service is advised that the digitally recorded data (unreduced) do have value for river regime and sediment transport assessments and provision is made for release to responsible authorities.

Bathymetric surveys conducted near high water, with auxiliary notes on bank conditions, could eliminate the necessity for major adjustment of surveyed or mapped waterlines. Satisfactory superimposition of repeated surveys would eliminate the need for photogrammetric mapping, since the technique demonstrated in Section 3.2 could then be applied over substantially the entire channel bed. For this to be effected, the navigation coordinates of the surveys must be absolute. This is not difficult to achieve with modern instruments. The interval between hydrographic surveys in the present day (7 or 8 years) appears to be satisfactory for sediment budget purposes.

During surveys, water levels should be kept at temporary gauges at several sites in the reach intended for sediment assessments, and these levels should be compared with those from the nearest regular gauging station.

For total load estimation, wash sediment load must be assessed in or near each reach, and the size range of the sediment determined. For purposes of estimating annual loads, it is not necessary to obtain a large number of samples (Church, et al, 1985, Appendix I). As few as 3 or 4 samples per season, over several years, should permit rating curves to be constructed adequately. The samples could, then, be obtained during gauge service visits or discharge metering. The composite sample from the river should be sufficiently large to permit grain size analysis. It serves no additional purpose to obtain texture analysis at individual

verticals. Table 5.1 lists gauge sites adjacent to proposed study reaches.

5.3.3 Special requirements, office:

If sediment transfer assessment by morphological means is to be established for Mackenzie River, a further effort should be made to interpret the historical materials in the most precise manner that is reasonable. In this study we have examined historical materials and it is evident that measurements at Norman Wells can be extended back for 1 decade and brought forward to date; that is, a record of over 40 years' duration could be obtained. Definitive computations would require some field results be available (i.e. full channel cross-sectional surveys, additional bed material textural analyses and some measurements of suspended load, as discussed in Section 5.3.1).

5.3.4. Continuing requirements, office:

It is not possible to say much about this topic, since the method for assessment of sediment transfers in the future will depend in major degree upon whether routine hydrographic surveys can be adapted to the purpose (cf. Section 5.3.2.). If this is the case, then a software system for receipt and processing of the data would be required.

There are two or three other river situations in Canada where similar arrangements may be possible (notably, the lower Fraser River and the St. Lawrence River in Lac St. Pierre), and the same system could be used to assess sedimentation in harbours. Hence, a quite general and therefore economical data analysis system is conceivable.

5.4 COSTS

The total budget for the present project was $15,000.00. Sediment transfer rates were investigated over 70 km of river which corresponsible to a cost of approximately $200/km.

The unit cost shown above is, however, not a reasonable basis for predicting the cost of undertaking similar projects in the future as:

i) Two of the principle objectives of this report were to a) locate and review the relevant mapping, aerial photography, bathymetry and sediment data and, except for newly acquired data, this information has been summarized for much of Mackenzie River in Appendices I, II and III, and b)significant amounts of time were required to develop the methodolgy used in this report. Future studies will benefit by this experience, although additional time may be required to write a computer program to compare repetitive bathymetric soundings or to undertake other tasks which were manually undertaken in the present study.

ii) Many of the expenses associated with the present study are not reflected in the budget. For example the Inland Waters Directorate provided all the required maps, charts and air photographs (estimated cost $1,000). In addition, the Geography Department, University of B.C. and M. Miles and Associates Ltd. donated the use of photogrammetric, digitizing and computer equipment which resulted in a considerable reduction in project costs.

iii) This study was partially undertaken as a research project and thus signficant amounts of professional time were donated by the principal investigators.

As a basis for estimating future project costs the following summary provides a listing of actual time and expenses accrued during the course of this study.

		Hours
Project Director (Church)	..	110
Geomorphologist (Miles)	..	190
Photogrammetrist (Rood)	..	200
Senior Technician (Goldsworthy	..	235
Draftsman (White)	..	85
Expenses (at cost)	..	$1300

If normal professional fees had been charged for all of these services, the project would have cost approximately $36,000.00 or $500/km. If similar analyses were to be undertaken in the future, the costs would probably be similar or slightly less than the unit cost/km shown above, as the expected saving in data compilation and development costs would likely be nearly offset by increased photogrammetric and computer expenses. Future, definitive, studies should however incorporate a field data collection program (as discussed in Section 5.3.3) and this would significantly increase the total budget requirements.

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6.2 Personal Communications

Mr. C.P. Lewis	Head, Physical Processes Unit Fisheries Branch B.C. Ministry of Environment Victoria, B.C.
Mr. F.J. Quinn, P. Eng.	Manager, Marine Surveys Terra Surveys Ltd. Sidney, B.C.

APPENDIX I

Summary of Hydrographic Data and Aerial Photography

NOTE:

Available aerial photographs have only been listed for the 190 km section of Mackenzie River between Great Bear River and Mountain River

CHS CHART: 6417

SUMMARY OF AVAILABLE INFORMATION

MILE 500 TO 530

1: HYDROGRAPHIC DATA

CHART	FIELD SHEET	YEAR	DATE	SCALE	COMMENTS
	3393	1964		1:65,000	reconnaissance survey; data limited to 3 or 4 transect lines down the main stem of the river
	3394	1964		1:65,000	
6417-73	3374	1973	Sep.	1:50,000	

2: AERIAL PHOTOGRAPHY

YEAR	FLYING HEIGHT (ft)	FOCAL LENGTH (in)	SCALE	AIR PHOTO INDEX NUMBER	COMMENTS
1944	14,000	8.3	1:20,000	96C-A	north half of map
1945	14,000	8.3	1:20,000	96C-A	south half of map
1944	14,000	8	1:20,000	96C-B	Fort Norman area only
1949	20,000	6	1:40,000	96C-B	
1961	5,300	6	1:10,000	96C-C	Fort Norman area only
1961	20,300	6	1:40,000	96C-no #	
1961	20,000	6	1:40,000	96SW-B	
1965	6,300	6	1:12,000	96C-C	Fort Norman area only
1969	6,300	6	1:12,000	IR96C-A	Fort Norman area only
1970	35,000	6	1:70,000	96C-C	
1972	6,500	6	1:12,000	96C-E	
1972	9,200	6	1:18,000	96C-F	Fort Norman area only
1972	18,500	6	1:37,000	96C-G	
1972	18,400	6	1:37,000	96C-G	
1972	6,500	6	1:12,000	96C-H	
1972	4,000	6	1: 8,000	96C-no #	Fort Norman area only
1973	6,500	6	1:12,000	96C-U	Fort Norman area only
1973	6,500	6	1:12,000	IR96C-C	Fort Norman area only
1974	30,000	6	1:60,000	96C-I	
1974	8,200	6	1:16,000	96C-J	
1974	5,000	6	1:10,000	96C-J	Fort Norman area only
1974	5,000	6	1:10,000	96C-J	

YEAR	FLYING HEIGHT (ft)	FOCAL LENGTH (in)	SCALE	AIR PHOTO INDEX NUMBER	COMMENTS
1974	10,430	6	1:20,000		
1974	10,000	6	1:20,000	96C-M	
1974	10,000	6	1:20,000	96C-N	
1974	5,000	6	1:10,000	96C-N	Fort Norman area only
1974	5,000	6	1:10,000	96C-O	Fort Norman area only
1975	10,000	6	1:20,000	96C-P	Fort Norman area only
1975	5,000	6	1:10,000	96C-P	Fort Norman area only
1975	5,500	6	1:10,000	96C-Q	Fort Norman area only
1975	10,000	6	1:20,000	96C-R	Fort Norman area only
1975	5,500	6	1:10,000	96C-R	Fort Norman area only
1975	12,800	6	1:26,000	96C-S	Fort Norman area only
1975	3,300	6	1: 6,000	96C/13 A	Fort Norman area only
1976	8,500	6	1:17,000	96C-T	Fort Norman area only
1976	8,000	6	1:16,000	96C-T	Fort Norman area only
1976	3,600	6	1: 7,000	96C-T	Fort Norman area only
1978	3,330	6	1: 7,000	96C-H	Fort Norman area only
1979	10,000	6	1:20,000	96C-V	
1979	3,500	6	1: 7,000	96C/13 B	Fort Norman area only
1979	3,500	6	1: 7,000	96C/13 C	Fort Norman area only
1979	4,000	6	1: 8,000	96C/13 D	Fort Norman area only
1980	2,750	6	1: 6,000	96C/13 E	Fort Norman area only
1980	2,750	6	1: 6,000	96C/14 A	Fort Norman area only
1983	11,000	6	1:22,000	96C-K	
1983	3,600	6	1: 7,000	96C-L	Fort Norman area only
1983	10,000	6	1:20,000	96C-L	
1983	13,100	6	1:26,000	96C-W	Fort Norman area only
1983	5,400	6	1:11,000	96C-X	Fort Norman area only
1983	2,750	6	1: 6,000	96C/13 F	Fort Norman area only
1983	2,750	6	1: 6,000	96C/14 B	Fort Norman area only

NOTES: 96C-D and 96SW-A not available for viewing.

CHS CHART: 6418

SUMMARY OF AVAILABLE INFORMATION

MILE 530 TO 575

1: HYDROGRAPHIC DATA

CHART	FIELD SHEET	YEAR	DATE	SCALE	COMMENTS
6418-73	3373	1973	Aug.	1:50,000	

2: AERIAL PHOTOGRAPHY

YEAR	FLYING HEIGHT (ft)	FOCAL LENGTH (in)	SCALE	AIR PHOTO INDEX NUMBER	COMMENTS
1944	14,000	8.3	1:21,000	96D-C	could be 6" focal length
1944	14,000	8	1:21,000	96E/1-16B	
1944	14,000	8	1:21,000	96E-E	Norman Wells only
1945	14,000	8	1:21,000	96E/1-16B	
1946	14,000	8	1:21,000	96E/1-16B	
1949	20,000	6	1:40,000	96D-B	
1949	20,000	6	1:40,000	96D-C	
1950	20,000	6	1:40,000	96E-E	
1950	(8,220)	(6)	scale unknown	96E-E	Norman Wells only
1951	20,000	6	1:40,000	96E-E	Norman Wells only
1961	20,300	6	1:40,000	96D-D	
1961	20,000	6	1:40,000	96SW-B	
1961	5,200	6	1:10,000	96E-D	Norman Wells only
1961	20,300	6	1:40,000	96E-D	Norman Wells only
1962	20,000	6	1:40,000	96SW-B	
1962	20,000	6	1:40,000	96E-D	Norman Wells only
1965	6,300	6	1:12,000	96E-E	Norman Wells only
1969	6,300	6	1:12,000	IR96E/A	Norman Wells only
1970	35,000	6	1:70,000	96D-D	
1971	26,000	6	1:50,000	96E-G	
1972	9,200	6	1:20,000	96D-F	Halfway Island only
1972	10,400	6	1:20,000	96E-H	
1972	3,900	6	1: 8,000	96E-H	Norman Wells only

YEAR	FLYING HEIGHT (ft)	FOCAL LENGTH (in)	SCALE	AIR PHOTO INDEX NUMBER	COMMENTS
1972	10,160	6	1:20,000	96E-I	north of Norman Wells
1972	9,200	6	1:20,000	96E-I	south of Norman Wells
1972	18,400	6	1:40,000	96E-J	
1972	18,600	6	1:40,000	96E-J	
1972	6,500	6	1:12,000	96E-J	north side river only
1972	6,500	6	1:12,000	96E-K	complete, except north bank only in vicinity of Norman Wells
1973	10,200	6	1:20,000	96D-G	
1973	5,000	6	1:10,000	96D-H	
1973	10,430	6	1:20,000	96D-H	
1973	10,200	6	1:20,000	96E-F	
1973	5,000	6	1:10,000	96E-F	
1973	5,000	6	1:10,000	96E-M	full coverage except north Rader Island
1973	10,200	6	1:20,000	96E-M	Rader Island and north
1974	10,000	6	1:20,000	96D-J	Partial coverage - vicinity Halfway Island
1974	10,000	6	1:20,000	96D-K	Partial coverage - vicinity Halfway Island
1974	10,000	6	1:20,000	96D-L	Partial coverage - vicinity Halfway Island
1974	10,000	6	1:20,000	96E-P	Ten Mile, Halfway and Rader Islands only
1974	10,000	6	1:20,000	96E-Q	
1974	5,000	6	1:10,000	96E-R	Norman Wells only
1974	10,000	6	1:20,000	96E-R	Ten Mile Island north
1974	10,000	6	1:20,000	96E-S	
1974	5,000	6	1:10,000	96E-S	Norman Wells only
1974	23,000	6	1:46,000	96E-T	Norman Wells only
1975	5,500	6	1:11,000	96D-M	
1975	5,000	6	1:10,000	96E-U	Norman Wells only
1976	3,600	6	1: 7,000	96E-W	Norman Wells only
1977	10,000	6	1:20,000	96D-O	south of Halfway Island
1977	5,000	6	1:10,000	96D-O	south of Halfway Island
1977	3,600	6	1: 7,000	96E-V	Norman Wells only
1978	3,600	6	1: 7,000	96E-P	Norman Wells only
1979	10,000	6	1:20,000	96D-N	south of Halfway Island
1979	10,000	6	1:20,000	96E-O	Norman Wells and north
1979	10,000	6	1:20,000	96E-X	Norman Wells only
1979	11,000	6	1:22,000	96E-Y	Norman Wells only
1980	10,200	6	1:20,000	96E-L	full coverage except for Halfway Island
1980	7,200	6	1:14,000	96-E6/A	Norman Wells north

YEAR	FLYING HEIGHT (ft)	FOCAL LENGTH (in)	SCALE	AIR PHOTO INDEX NUMBER	COMMENTS
1980	7,200	6	1:14,000	96-E6/B	Norman Wells north
1980	2,740	6	1: 6,000	96-E7/C	Norman Wells only
1981	2,700	6	1: 6,000	96-E7/D	Norman Wells only
1981	2,500	6	1: 5,000	96E-AA	Norman Wells only
1981	10,000	6	1:20,000	96E-AA	Norman Wells only
1982	2,000	6	1: 4,000	96-E7/E	Norman Wells only
1982	3,300	6	1: 7,000	96-E7/F	Norman Wells only
1983	2,750	6	1: 6,000	96-E7/G	Norman Wells only
1983	10,500	6	1:20,000	96E-AB	Norman Wells only

NOTES: 96D-A, 96SW-A and 96E/1-16A not available for viewing.

CHS CHART: 6419

SUMMARY OF AVAILABLE INFORMATION

MILE 565 TO 608

1: HYDROGRAPHIC DATA

CHART	FIELD SHEET	YEAR	DATE	SCALE	COMMENTS
6419-71	3360	1971	Aug.	1:50,000	
	6419-78	1978	Jun/Jul	1:50,000	

2: AERIAL PHOTOGRAPHY

YEAR	FLYING HEIGHT (ft)	FOCAL LENGTH (in)	SCALE	AIR PHOTO INDEX NUMBER	COMMENTS
1944	14,000	8	1:21,000	96E/1-16B	
1944	14,000	8	1:21,000	96E-E	Norman Wells only
1945	14,000	8	1:21,000	96E/1-16B	
1946	14,000	8	1:21,000	96E/1-16B	
1950	20,000	6	1:40,000	96E-E	
1950	(8,230)	(6)	scale unknown	96E-E	Norman Wells only
1951	20,000	6	1:40,000	96E-E	Patricia Island and Norman Wells only
1961	5,200	6	1:10,000	96E-D	Norman Wells only
1961	20,300	6	1:40,000	96E-D	Norman Wells only
1962	20,000	6	1:40,000	96SW-B	
1962	20,000	6	1:40,000	96E-D	
1965	6,300	6	1:12,000	96E-E	Norman Wells only
1967	20,000	6	1:40,000	96SW-B	
1967	20,000	6	1:40,000	96E-D	Patricia Island north
1969	6,300	6	1:12,000	IR96E-A	Norman Wells only
1970	35,000	6	1:70,000	96E-D	Patricia Island north
1971	26,000	6	1:50,000	96E-G	
1972	10,400	6	1:20,000	96E-H	
1972	3,900	6	1: 8,000	96E-H	Norman Wells only
1972	10,160	6	1:20,000	96E-I	
1972	6,500	6	1:12,000	96E-J	north side river only
1972	19,000	6	1:40,000	96E-J	north side river only

YEAR	FLYING HEIGHT (ft)	FOCAL LENGTH (in)	SCALE	AIR PHOTO INDEX NUMBER	COMMENTS
1972	6,500	6	1:12,000	96E-K	full coverage except north bank only in the vicinity Perry Island
1972	18,500	6	1:40,000	96E-N	Ogilvie Island north
1973	5,000	6	1 10,000	96E-M	Norman Wells only
1973	10,200	6	1:20,000	96E-M	Norman Wells only
1973	10,200	6	1:20,000	96E-F	
1973	5,000	6	1:10,000	96E-F	Norman Wells only
1973	6,500	6	1:12,000	96E-X	Judith Island to Ogilvie Island
1974	10,000	6	1:20,000	96E-P	Rader Island to Perry Island
1974	10,000	6	1:20,000	96E-Q	Norman Wells to Ogilvie Island
1974	10,000	6	1:20,000	96E-R	Norman Wells to Ogilvie Island
1974	5,000	6	1:10,000	96E-R	Norman Wells only
1974	5,000	6	1:10,000	96E-S	Norman Wells only
1974	10,000	6	1:20,000	96E-S	Norman Wells to Perry Island
1974	23,000	6	1:46,000	96E-T	Norman Wells only
1975	5,000	6	1:10,000	96E-U	Norman Wells only
1975	10,000	6	1:20,000	96E-U	Rader Island to Ogilvie Island
1976	3,600	6	1: 7,000	96E-W	Norman Wells only
1977	3,600	6	1: 7,000	96E-V	Norman Wells only
1978	3,600	6	1: 7,000	96E-P	Norman Wells only
1979	10,000	6	1:20,000	96E-O	Norman Wells to Ogilvie Island
1979	10,000	6	1:20,000	96E-X	Norman Wells only
1979	11,000	6	1:22,000	96E-Y	Norman Wells only
1980	10,200	6	1:20,000	96E-L	Norman Wells to Judith Island only
1980	7,200	6	1:15,000	96-E6/A	Ogilvie Island south
1980	7,200	6	1:15,000	96-E7/B	Ogilvie Island south
1980	2,740	6	1: 6,000	96-E7/C	Norman Wells only
1981	2,700	6	1: 6,000	96-E7/D	Norman Wells only
1981	10,000	6	1:20,000	96-E/AA	full coverage except for Patricia Island and Ogilvie Island
1981	2,500	6	1: 5,000	96-E/AA	Norman Wells only
1982	2,000	6	1: 4,000	96-E7/E	
1982	3,300	6	1: 7,000	96-E7/F	Norman Wells only
1983	2,750	6	1: 6,000	96-E7/G	Norman Wells only
1983	10,500	6	1:20,000	96-E/AB	Norman Wells only

NOTES: 96D-E, 96SW-A and 96E/1-16A not available for viewing

CHS CHART: 6420 & 6451

SUMMARY OF AVAILABLE INFORMATION

MILE 608 TO 645

1: HYDROGRAPHIC DATA

CHART	FIELD SHEET	YEAR	DATE	SCALE	COMMENTS
	2851 H-5	1958		1:7,200	Two sheets North & South
6420-71	3361	1971	Aug	1:50,000	
	6420-79	1979	Sep	1:50,000	Km 1030 to 1038 only
	6451-79	1979	Jul	1:1,000	Sans Sault Rapids only, approx. Km 1017

2: AERIAL PHOTOGRAPHY

YEAR	FLYING HEIGHT (ft)	FOCAL LENGTH (in)	SCALE	AIR PHOTO INDEX NUMBER	COMMENTS
1944	14,000	8	1:21,000	106H-A	
1945	14,000	8	1:21,000	106H-A	
1950	20,000	6	1:40,000	106H-C	
1951	20,000	6	1:40,000	106H-C	
1967	20,000	6	1:40,000	106H-E	
1970	35,000	6	1:70,000	106H-D	
1971	35,000	6	1:70,000	106H-F	
1972	6,220	6	1:12,000	106H-H	
1972	10,160	6	1:20,000	106H-L	south of Axel Island
1972	10,250	6	1:20,000	106H-I	
1972	10,270	6	1:20,000	106H-H	
1972	10,300	6	1:20,000	106H-H	
1972	10,340	6	1:20,000	106H-H	
1973	10,200	6	1:20,000	106H-M	
1974	10,000	6	1:20,000	106H-O	south of Axel Island
1981	10,000	6	1:20,000	106H-Q	south of Axel Island
1981	28,000	6	1:56,000	106H-R	

CHS CHART: 6421

SUMMARY OF AVAILABLE INFORMATION

MILE 645 TO 680

1: HYDROGRAPHIC DATA

CHART	FIELD SHEET	YEAR	DATE	SCALE	COMMENTS
6421-71	3362	1971	Aug	1:50,000	
	6421-77	1977	Jul	1:50,000	Mile 652 to 665 only
	6421-79	1979	Sep	1:50,000	Km 1054 to 1072 only

2: AERIAL PHOTOGRAPHY

YEAR	FLYING HEIGHT (ft)	FOCAL LENGTH (in)	SCALE	AIR PHOTO INDEX NUMBER	COMMENTS

CHS CHART: 6422

SUMMARY OF AVAILABLE INFORMATION

MILE 680 TO 735

1: HYDROGRAPHIC DATA

CHART	FIELD SHEET	YEAR	DATE	SCALE	COMMENTS
6422-72	3365	1972	Aug	1:50,000	
	6422-79	1979	Aug	1:50,000	

2: AERIAL PHOTOGRAPHY

YEAR	FLYING HEIGHT (ft)	FOCAL LENGTH (in)	SCALE	AIR PHOTO INDEX NUMBER	COMMENTS

CHS CHART: 6423

SUMMARY OF AVAILABLE INFORMATION

MILE 730 TO 767

1: HYDROGRAPHIC DATA

CHART	FIELD SHEET	YEAR	DATE	SCALE	COMMENTS
6423-73	3369-S	1973	Jun	1:50,000	
	6423-78	1978	?	1:50,000	Partial coverage; revision to chart 6423 at Mile 765
	6423-79	1979	Jul	1:50,000	

2: AERIAL PHOTOGRAPHY

YEAR	FLYING HEIGHT (ft)	FOCAL LENGTH (in)	SCALE	AIR PHOTO INDEX NUMBER	COMMENTS

CHS CHART: 6424

SUMMARY OF AVAILABLE INFORMATION

MILE 767 TO 820

1: HYDROGRAPHIC DATA

CHART	FIELD SHEET	YEAR	DATE	SCALE	COMMENTS
6424-72	3366	1972	Aug	1:50,000	
	6424A-77	1977	Aug/Sep	1:50,000	Mile 769 to 776
	6424B-77	1977	Sep	1:50,000	Mile 780 to 791
	6424-79	1979	Jul	1:50,000	

2: AERIAL PHOTOGRAPHY

YEAR	FLYING HEIGHT (ft)	FOCAL LENGTH (in)	SCALE	AIR PHOTO INDEX NUMBER	COMMENTS

CHS CHART: 6425

SUMMARY OF AVAILABLE INFORMATION

MILE 820 TO 865

1: HYDROGRAPHIC DATA

CHART	FIELD SHEET	YEAR	DATE	SCALE	COMMENTS
6425-73	3370	1973	Jul	1:50,000	
6425	--	1974	Aug	1:50,000	Barrel Crossing Mile 832
	6425-77	1977	Aug	1:50,000	Mile 832 to 838
	6425-78	1978	Aug/Sep	1:50,000	
	6425A-79	1979	Jul	1:50,000	Km 1324 to 1330
	6425B-79	1979	Jul	1:50,000	Km 1341 to 1354

2: AERIAL PHOTOGRAPHY

YEAR	FLYING HEIGHT (ft)	FOCAL LENGTH (in)	SCALE	AIR PHOTO INDEX NUMBER	COMMENTS

CHS CHART: 6426

SUMMARY OF AVAILABLE INFORMATION

MILE 865 TO 915

1: HYDROGRAPHIC DATA

CHART	FIELD SHEET	YEAR	DATE	SCALE	COMMENTS
6426-73	3371	1973	Aug	1:50,000	
	6426-77	1977	Aug	1:50,000	Mile 865 to 880
	6426-78	1978	Aug	1:50,000	Km 1422 to 1441

2: AERIAL PHOTOGRAPHY

YEAR	FLYING HEIGHT (ft)	FOCAL LENGTH (in)	SCALE	AIR PHOTO INDEX NUMBER	COMMENTS

APPENDIX II

Truncated Bed Material and Suspended Sediment Size Distributions

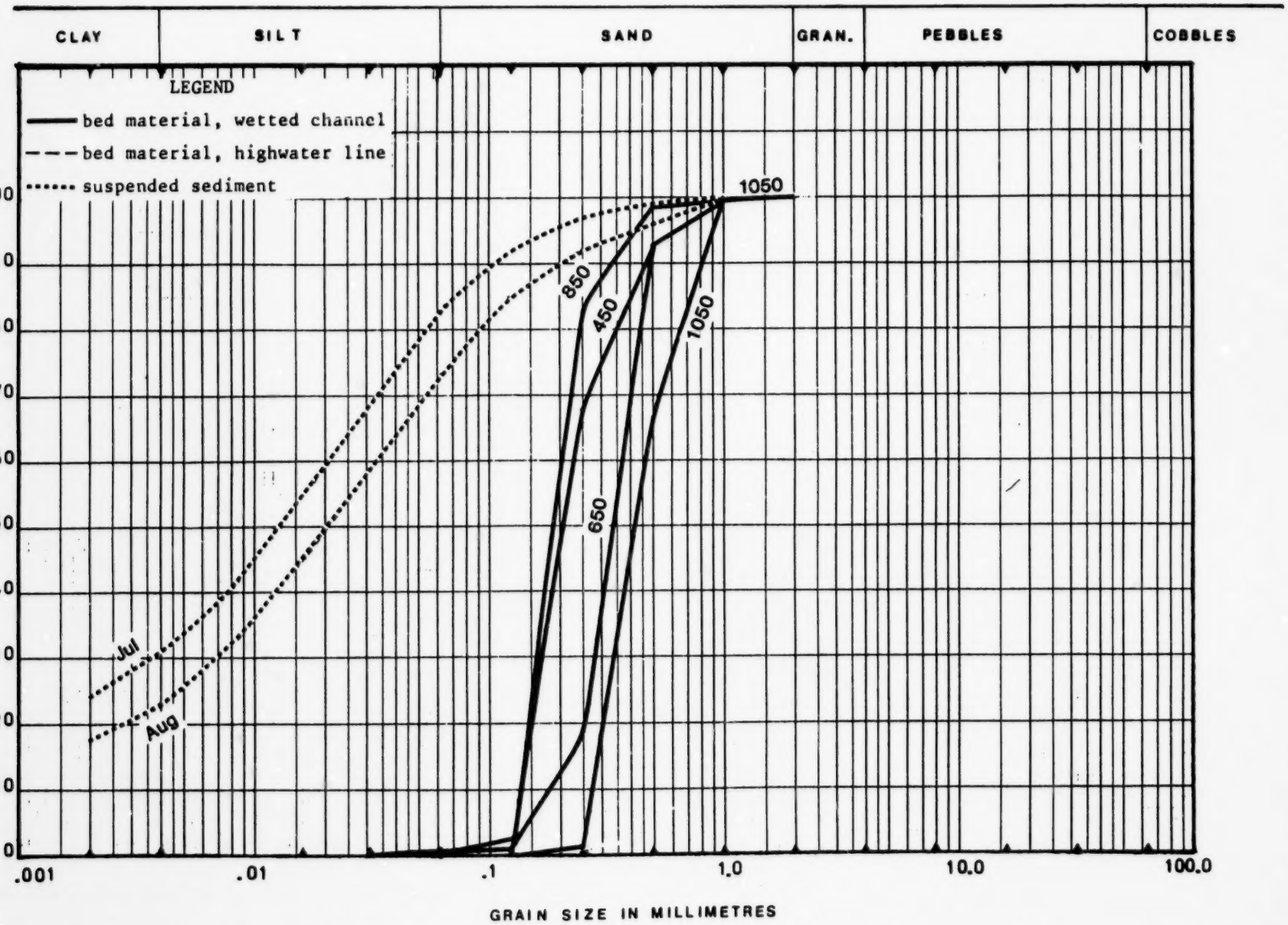

Figure AII-1: Truncated bed material and suspended sediment size distributions, Mackenzie River above Arctic Red River, 1972.

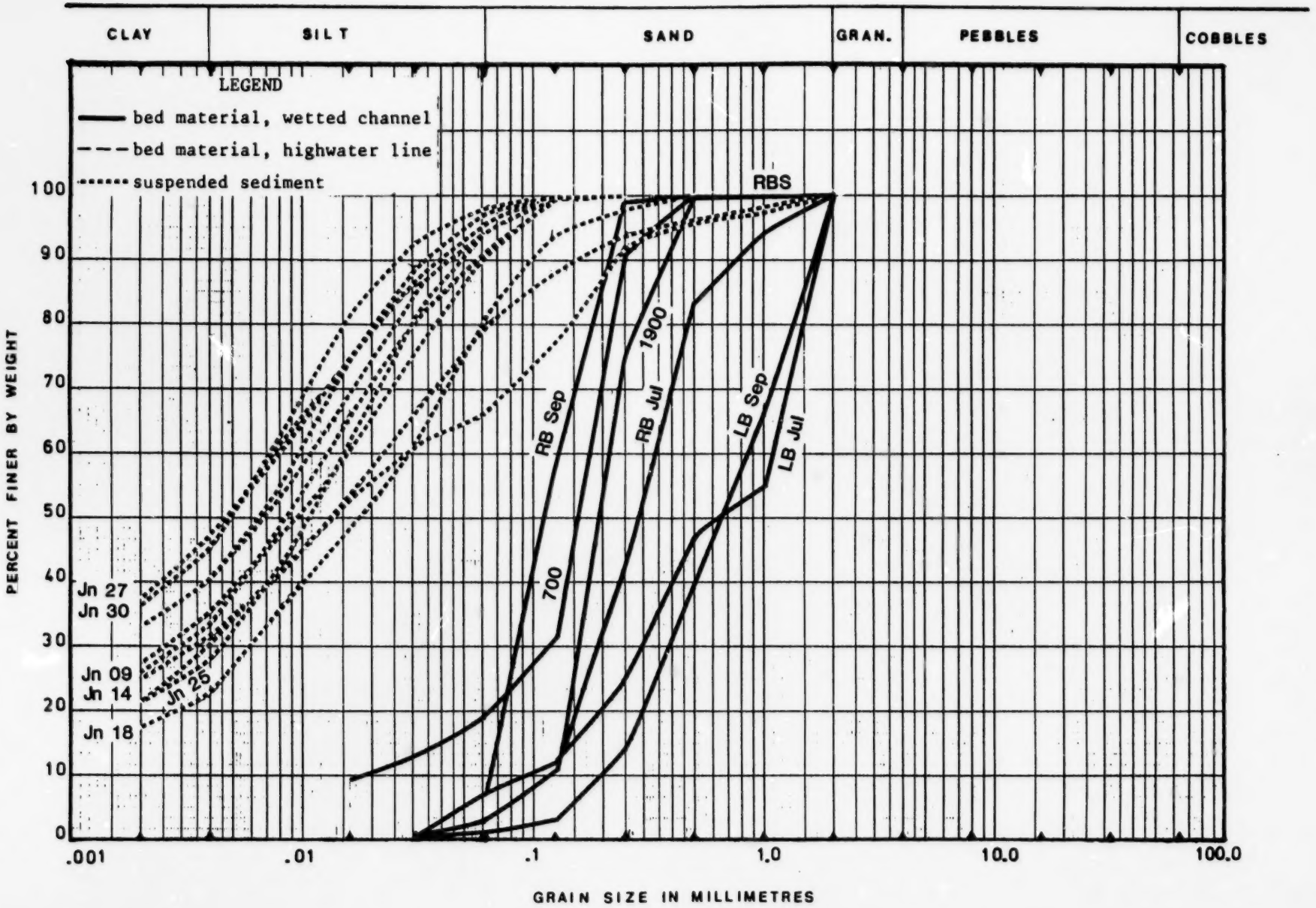

Figure AII-2: Truncated bed material and suspended sediment size distributions, Mackenzie River above Arctic Red River 1973.

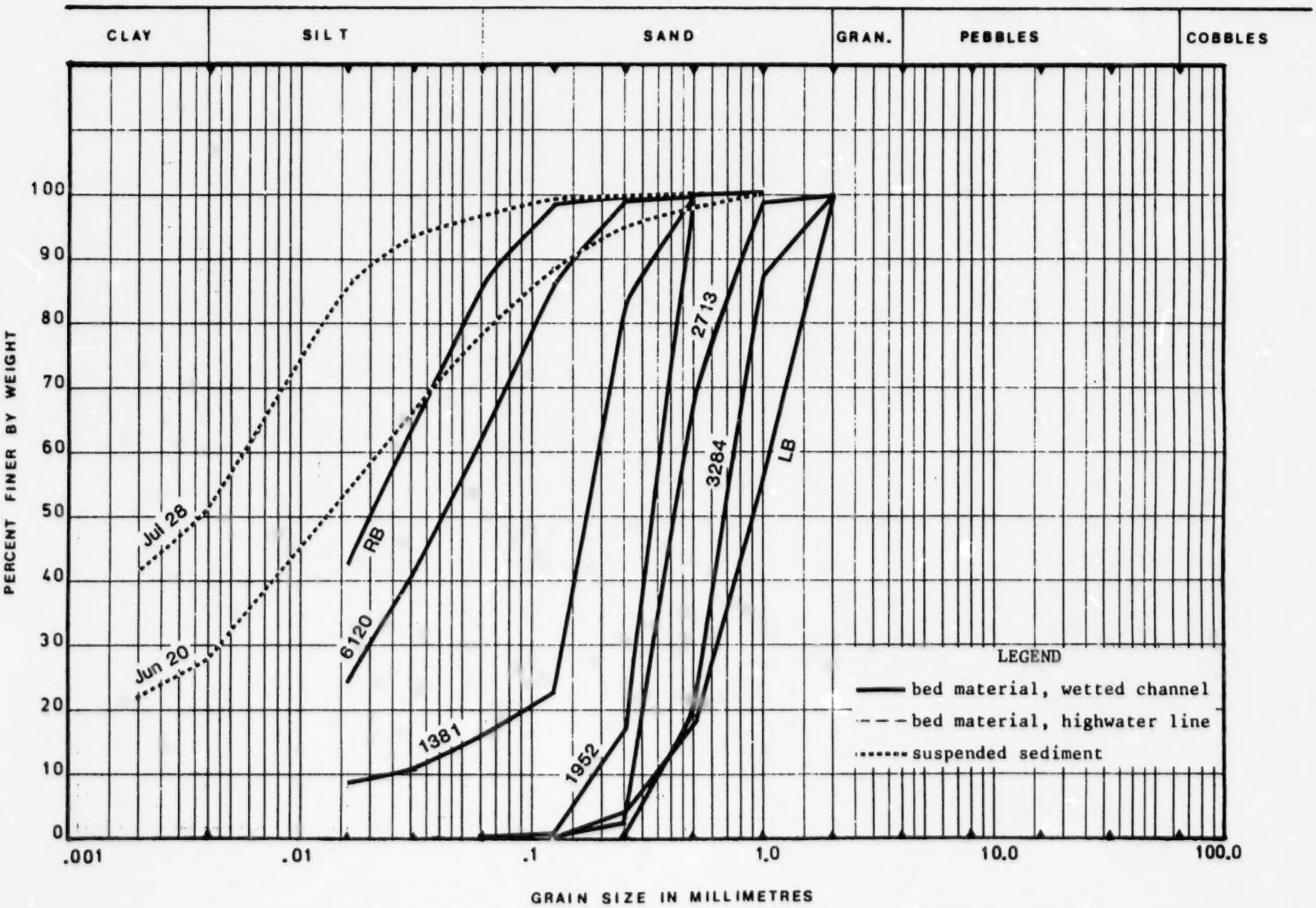

Figure AII-3: Truncated bed material and suspended sediment size distributions, Mackenzie River above Arctic Red River, 1974.

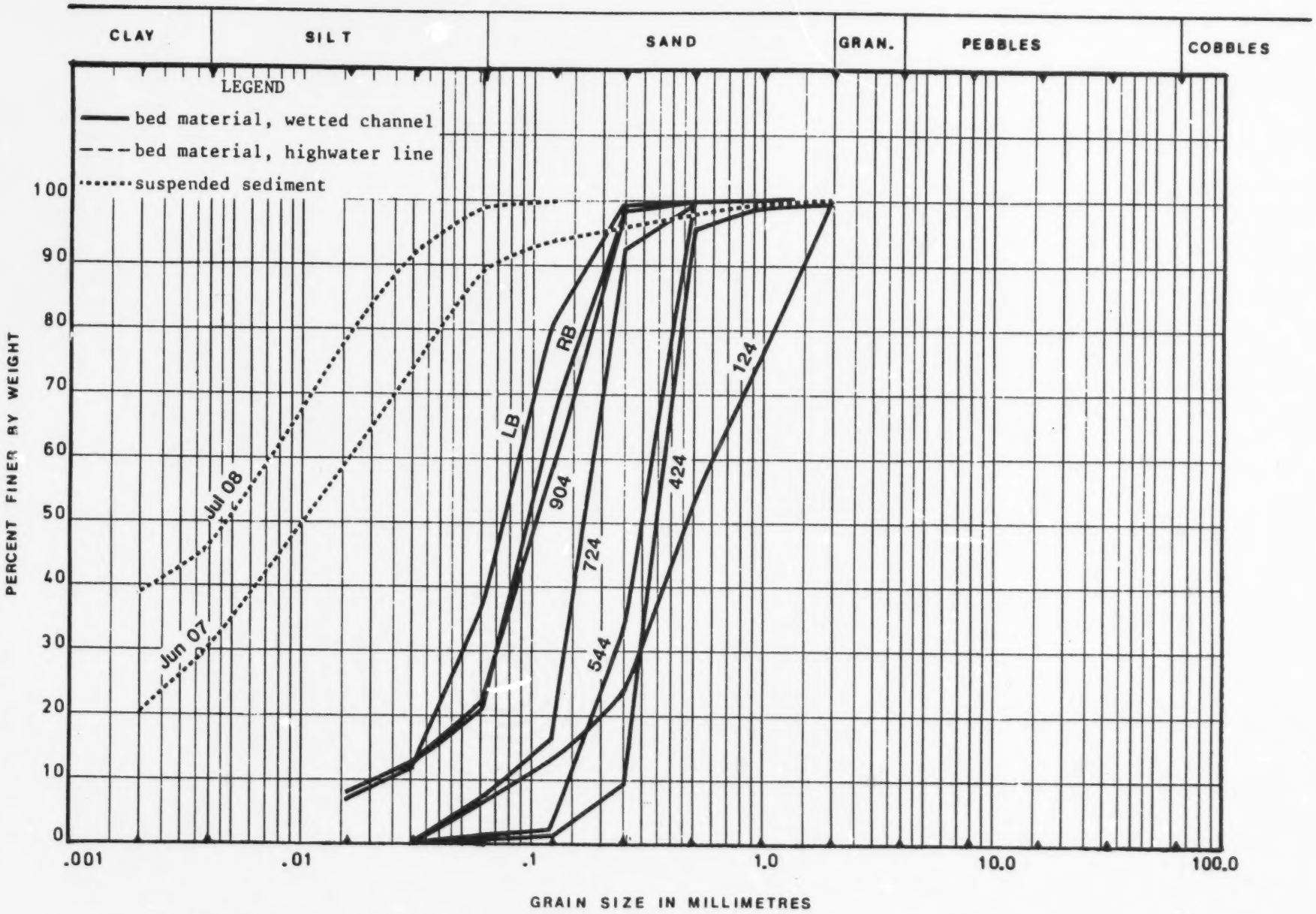

Figure AII-4: Truncated bed material and suspended sediment size distributions, Mackenzie River above Arctic Red River, 1975.

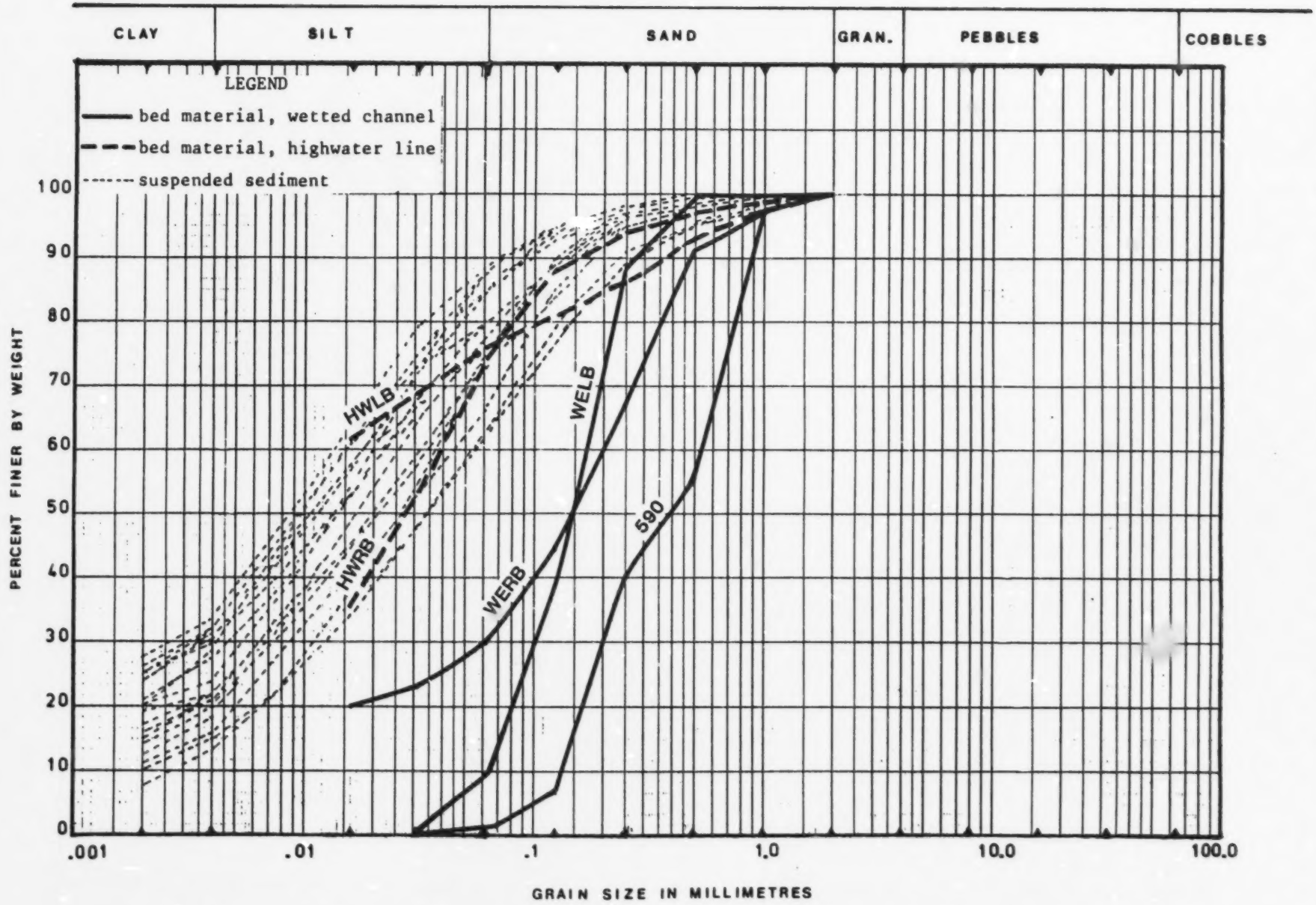

Figure AII-5: Truncated bed material and suspended sediment size distributions, Liard River near the Mouth, 1973.

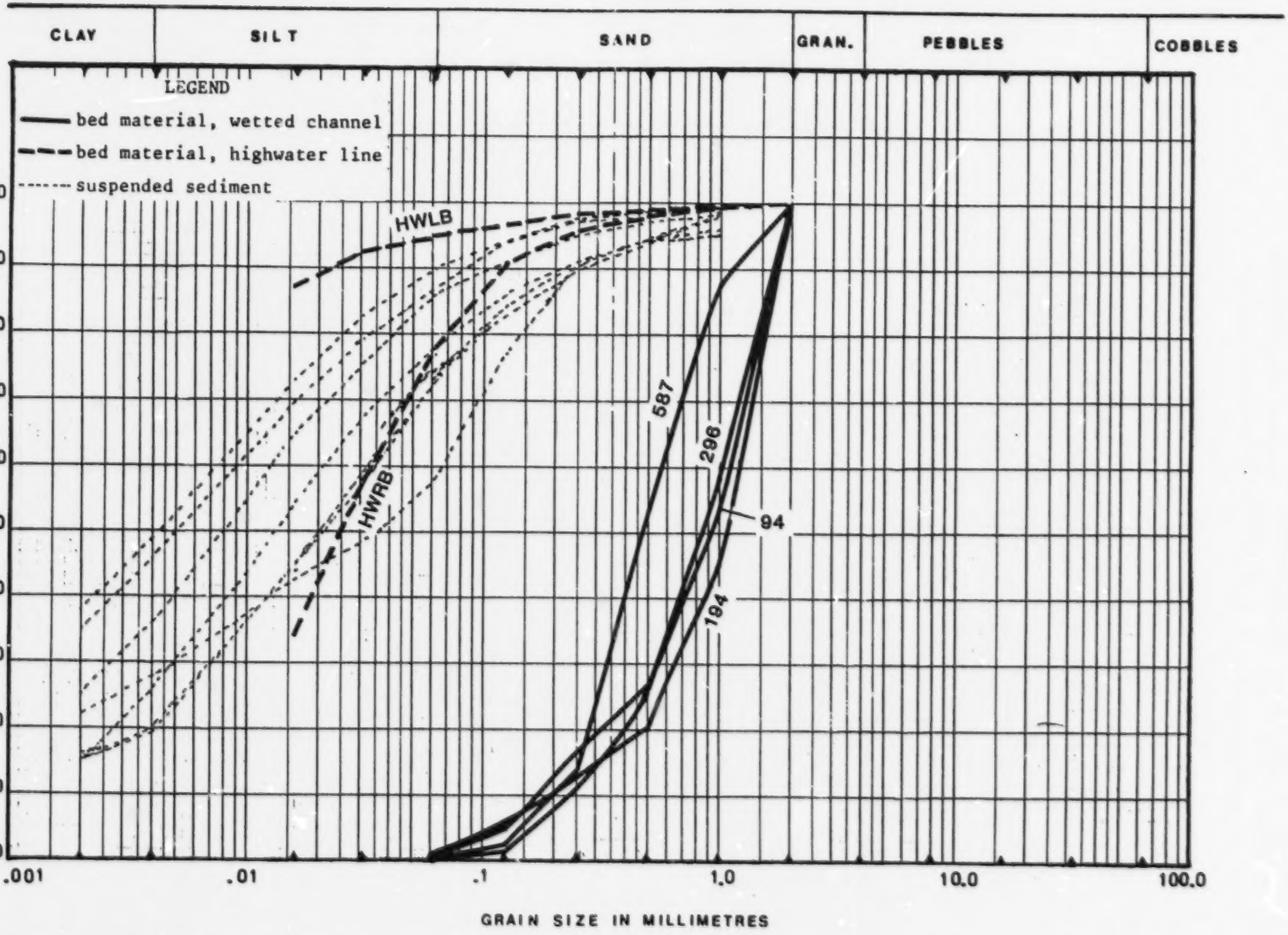

Figure AII-6: Truncated bed material and suspended sediment size distributions, Liard River near the Mouth, 1974.

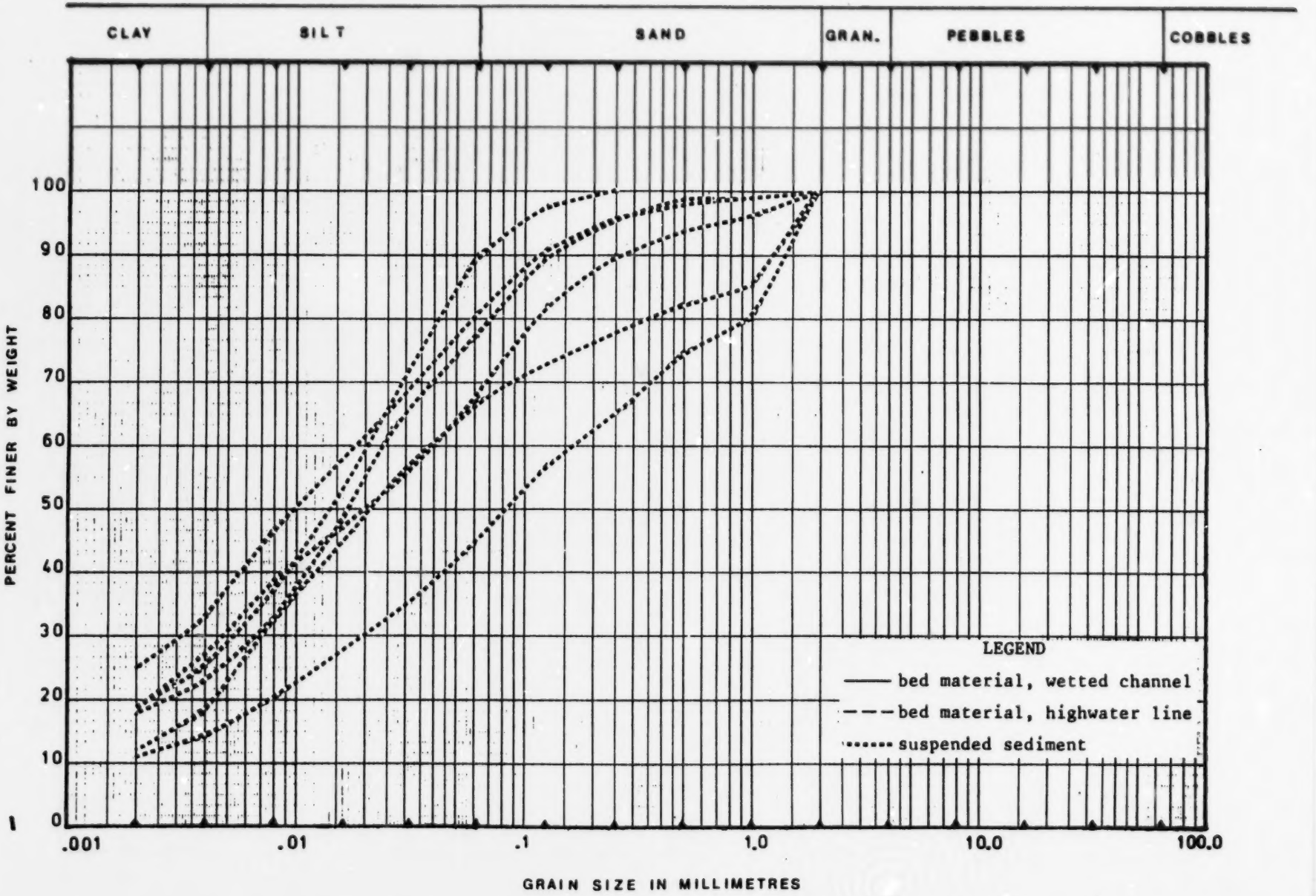

Figure AII-7: Suspended sediment size distribution at Norman Wells, 1973.

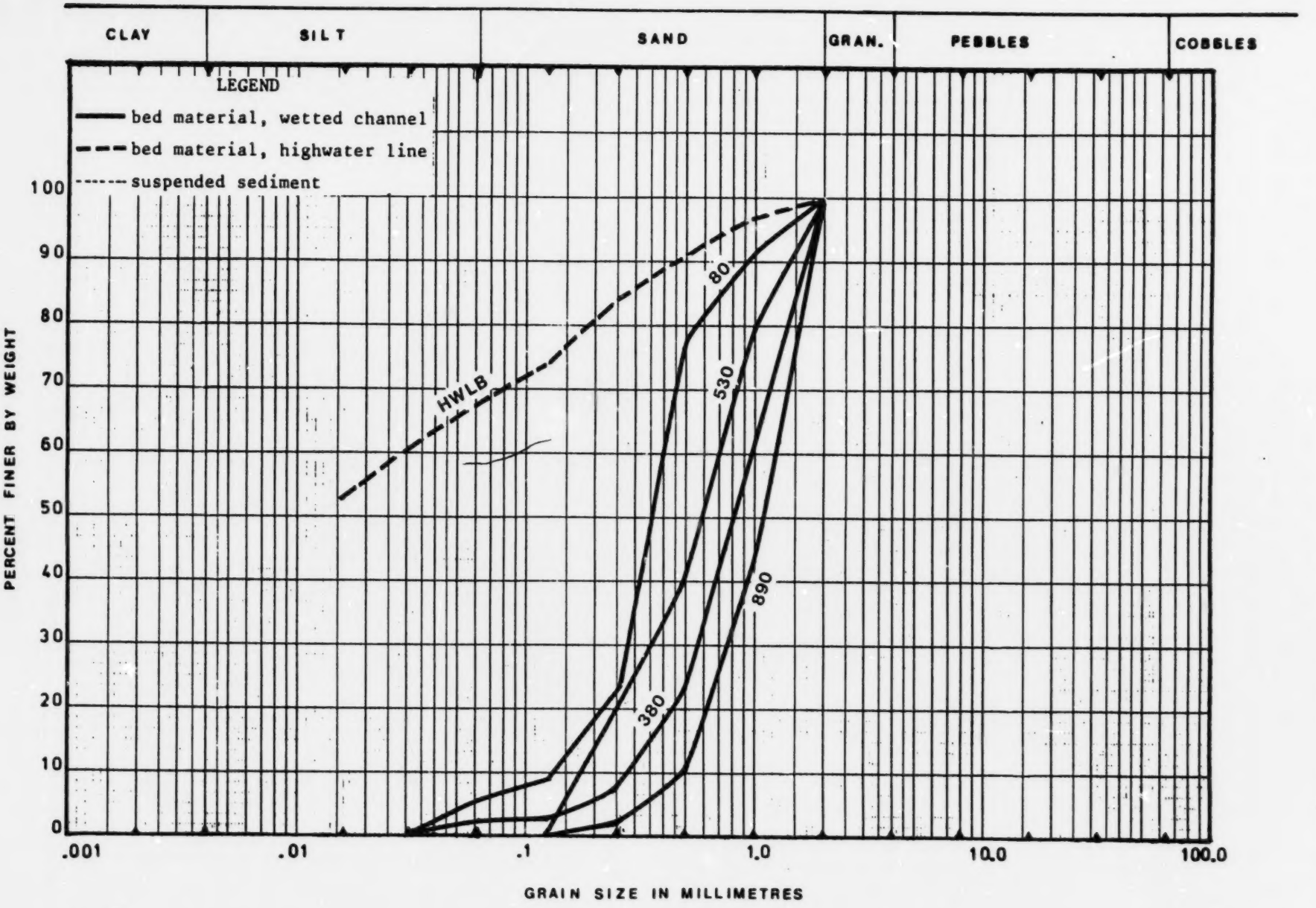

Figure AII-8: Truncated bed material size distribution, Mackenzie River above Liard River, 1974.

APPENDIX III

Complete Bed Material and Suspended Sediment Size Distributions

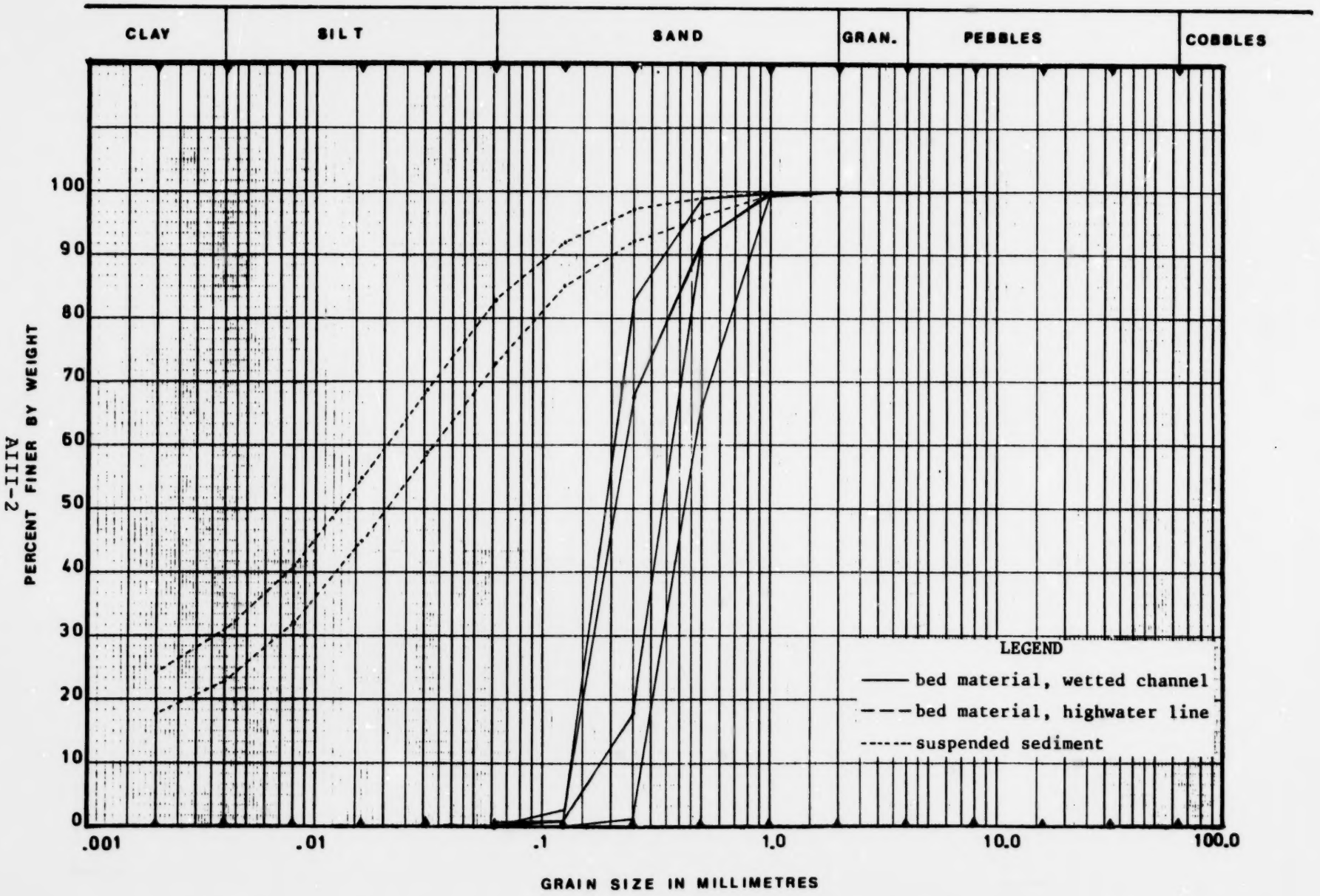

Figure AIII-1: Complete bed material and suspended sediment size distribution, Mackenzie River above Arctic Red River, 1972.

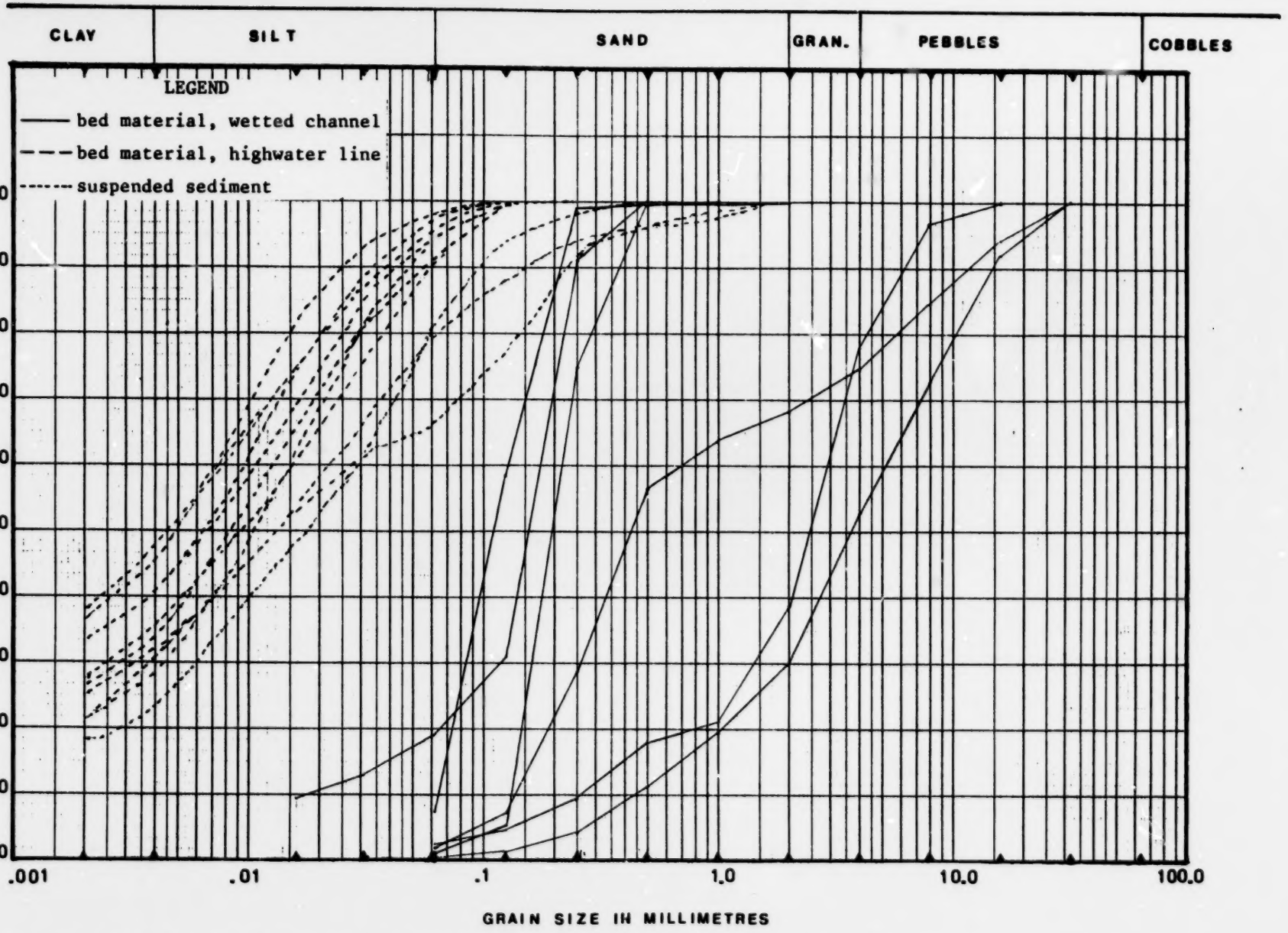

Figure AIII-2: Complete bed material and suspended sediment size distribution, Mackenzie River above Arctic Red River, 1973.

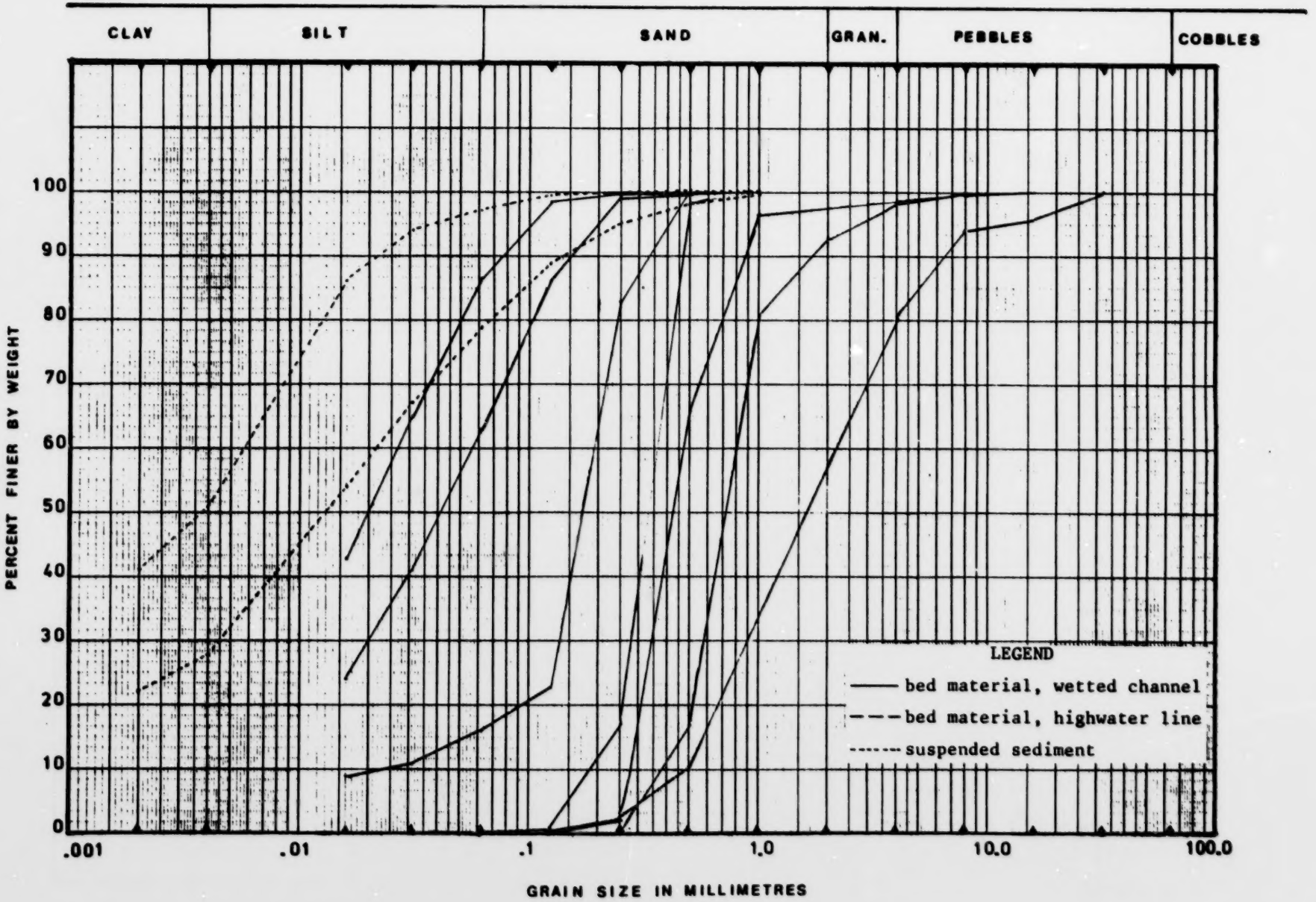

Figure AIII-3: Complete bed material and suspended sediment size distribution, Mackenzie River above Arctic Red River, 1974.

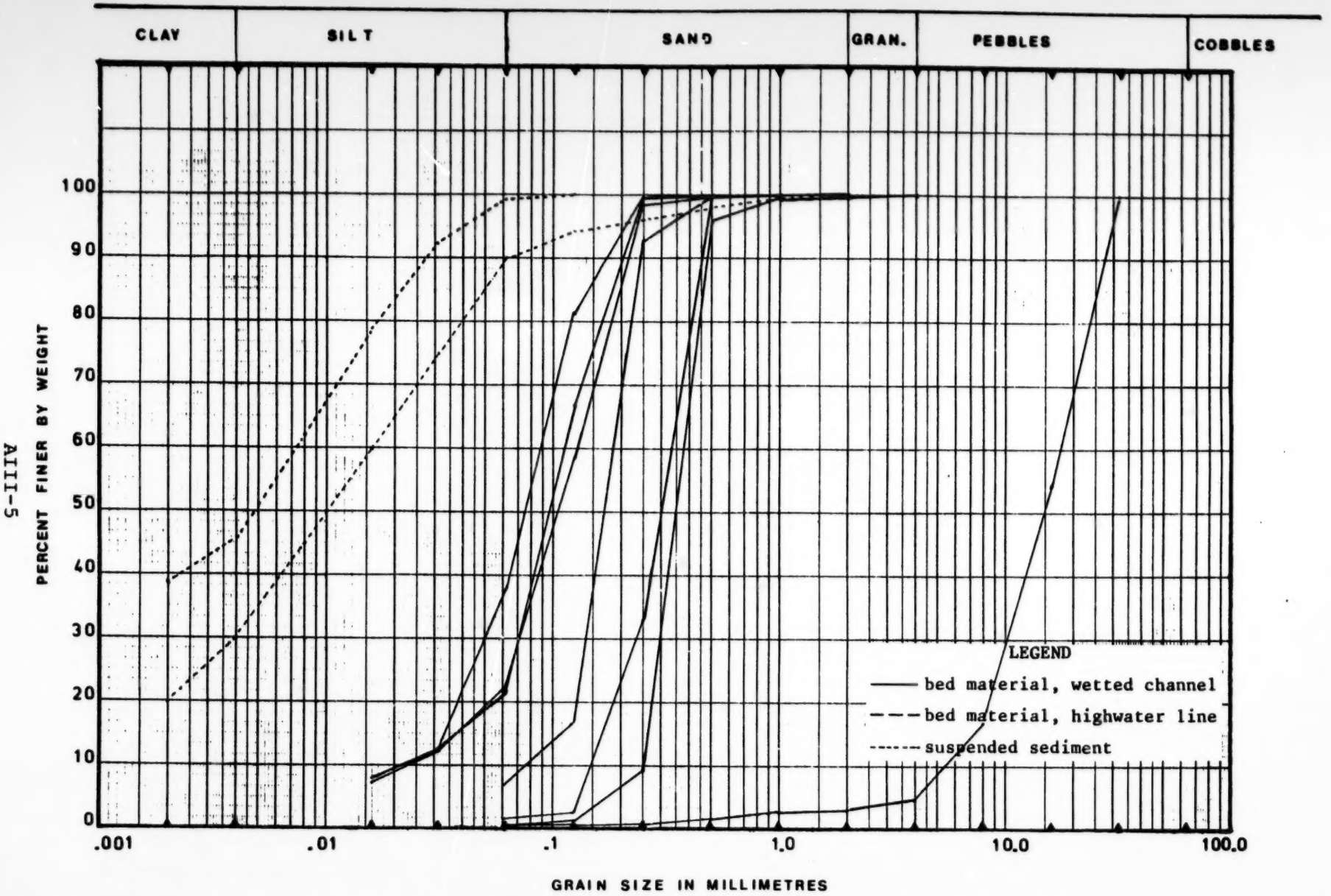

Figure AIII-4: Complete bed material and suspended sediment size distribution, Mackenzie River above Arctic Red River, 1975.

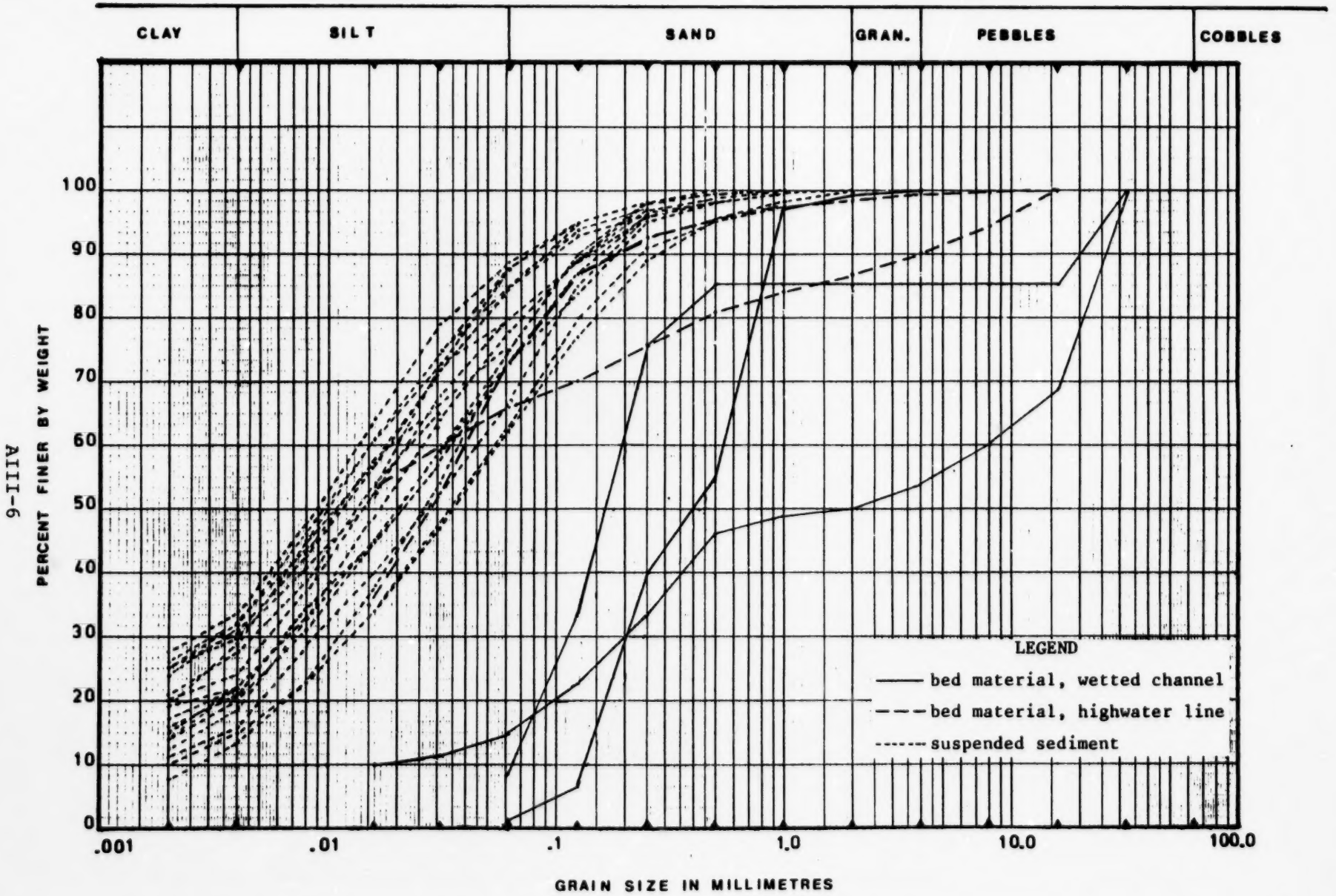

Figure AIII-5: Complete bed material and suspended sediment size distribution, Liard River near the Mouth, 1973.

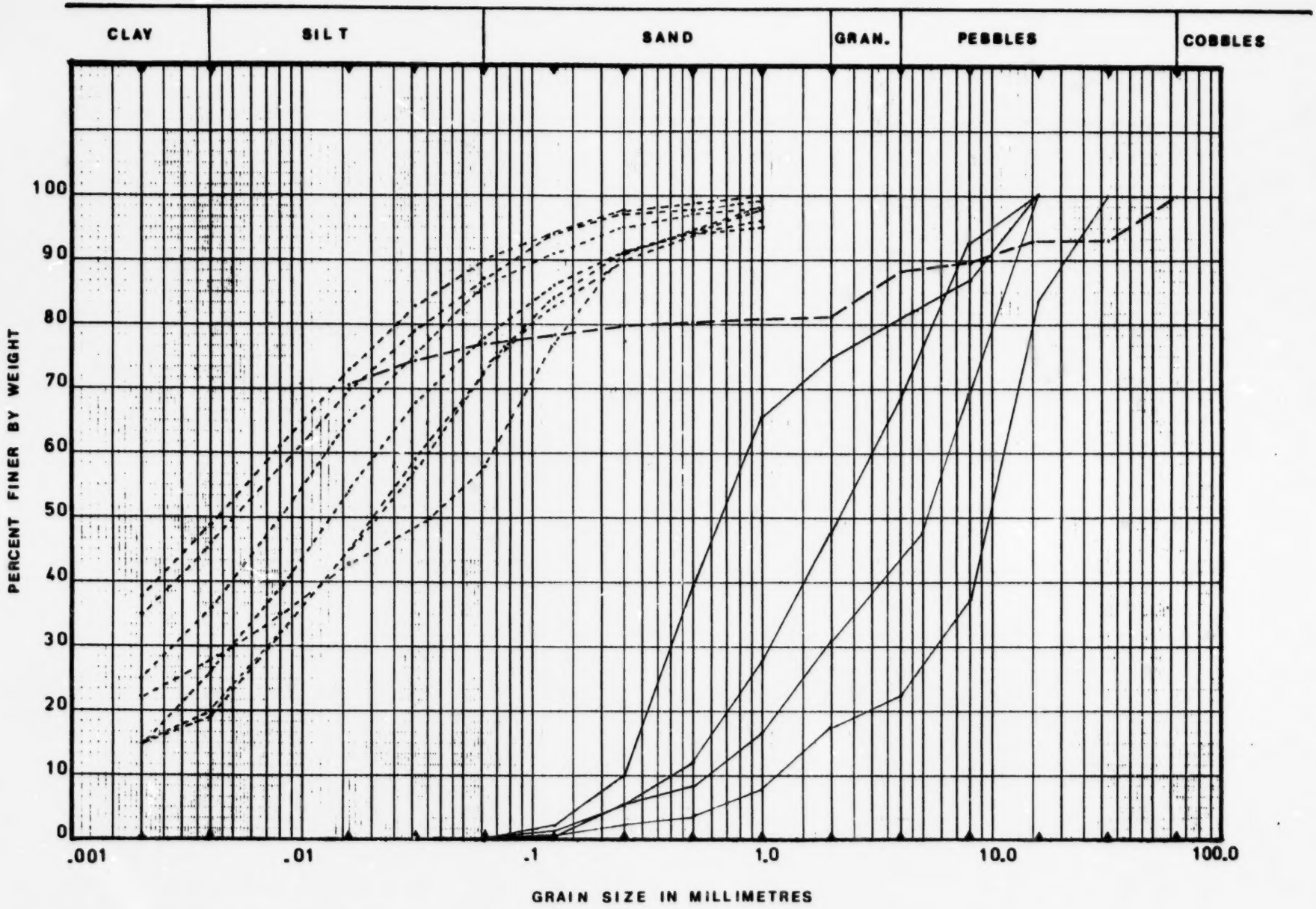

Figure AIII-6: Complete bed material and suspended sediment size distribution, Liard River near the Mouth, 1974.

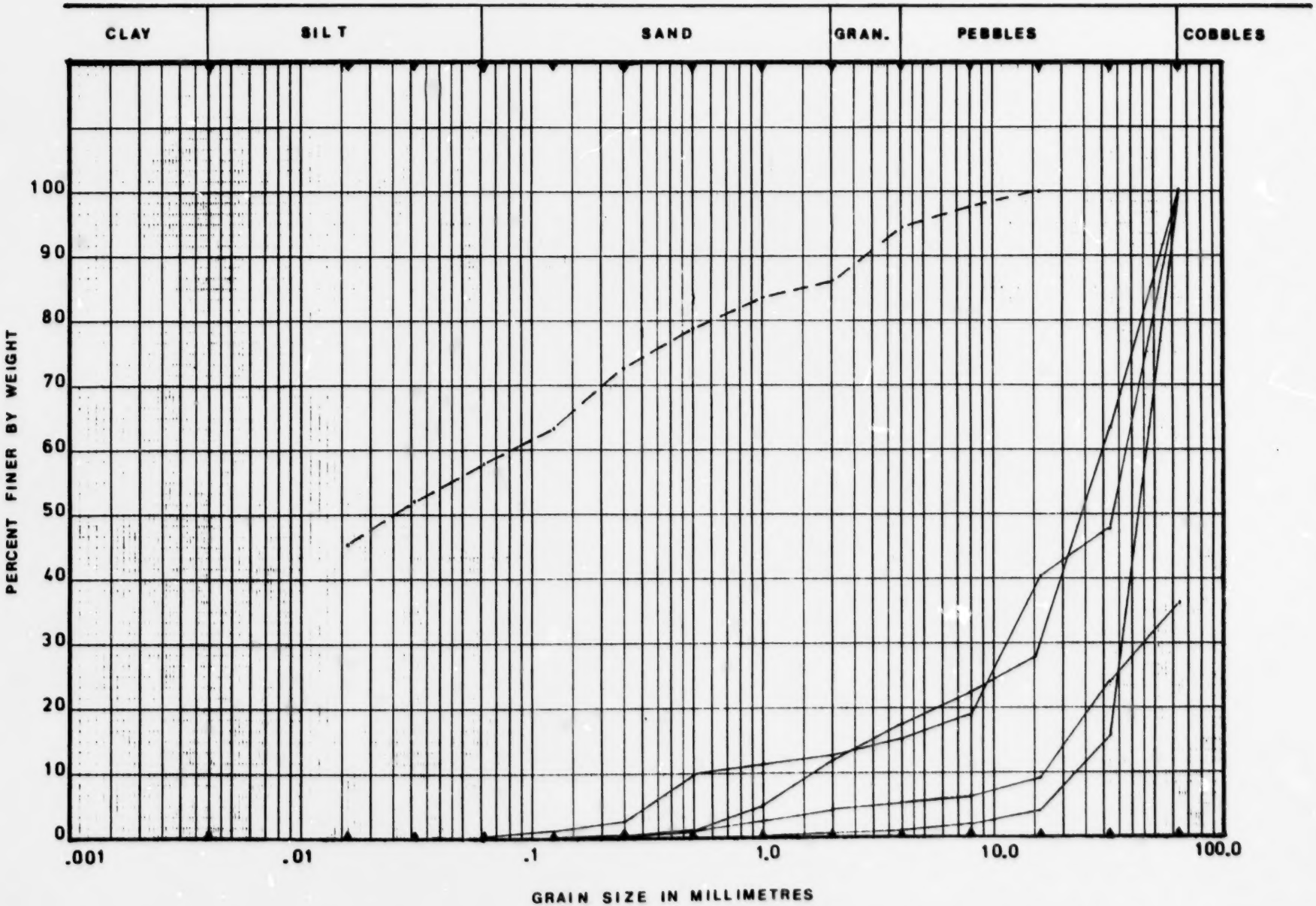

Figure AIII-7: Complete bed material size distribution, Mackenzie River above Liard River, 1974.

APPENDIX IV

Comparison of Complete and Truncated Bed Material Size Distributions

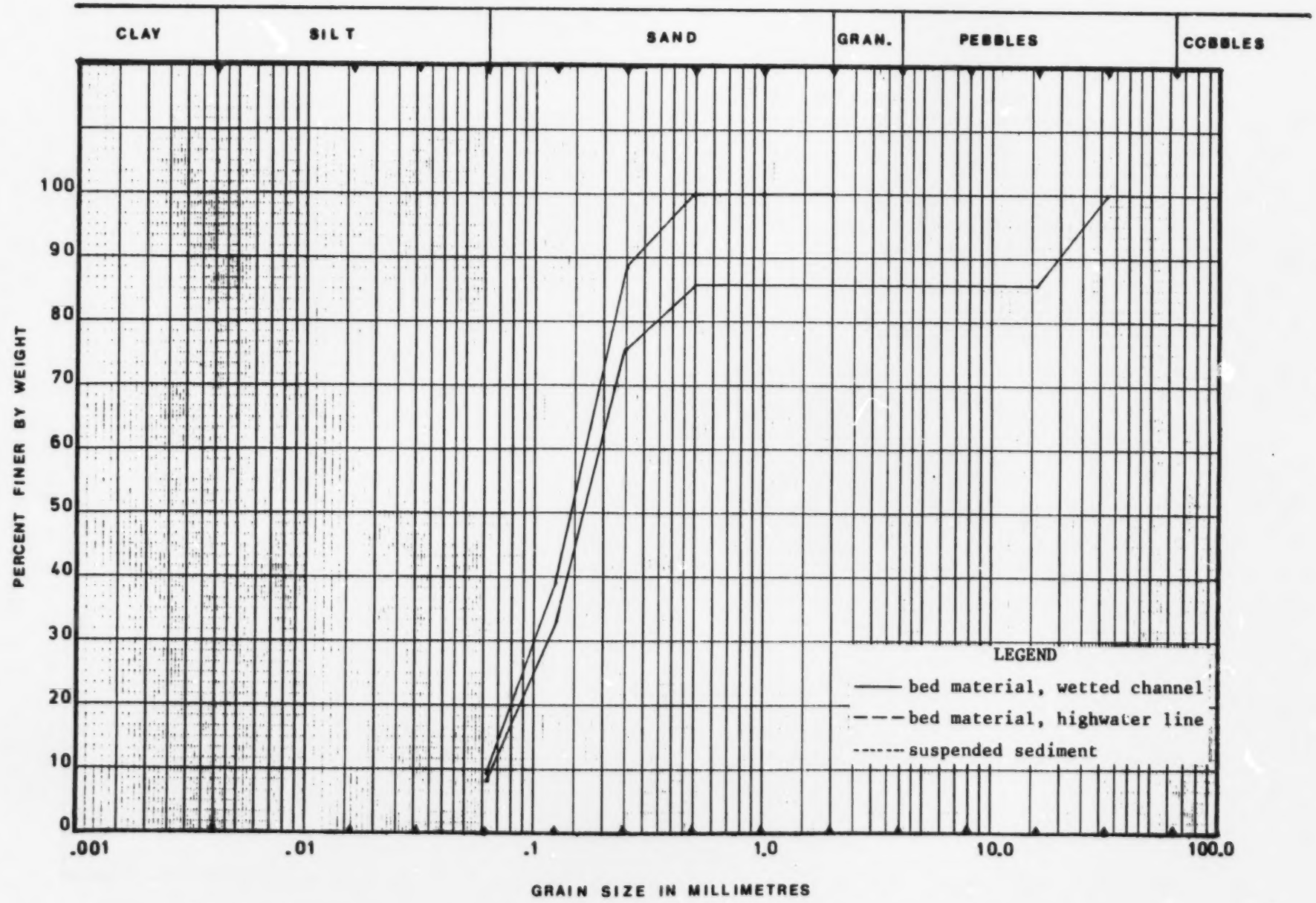

Figure AIV-1: Comparison of complete and truncated bed material size distributions, Liard River near the Mouth, 1973. Sample Location - WELB.

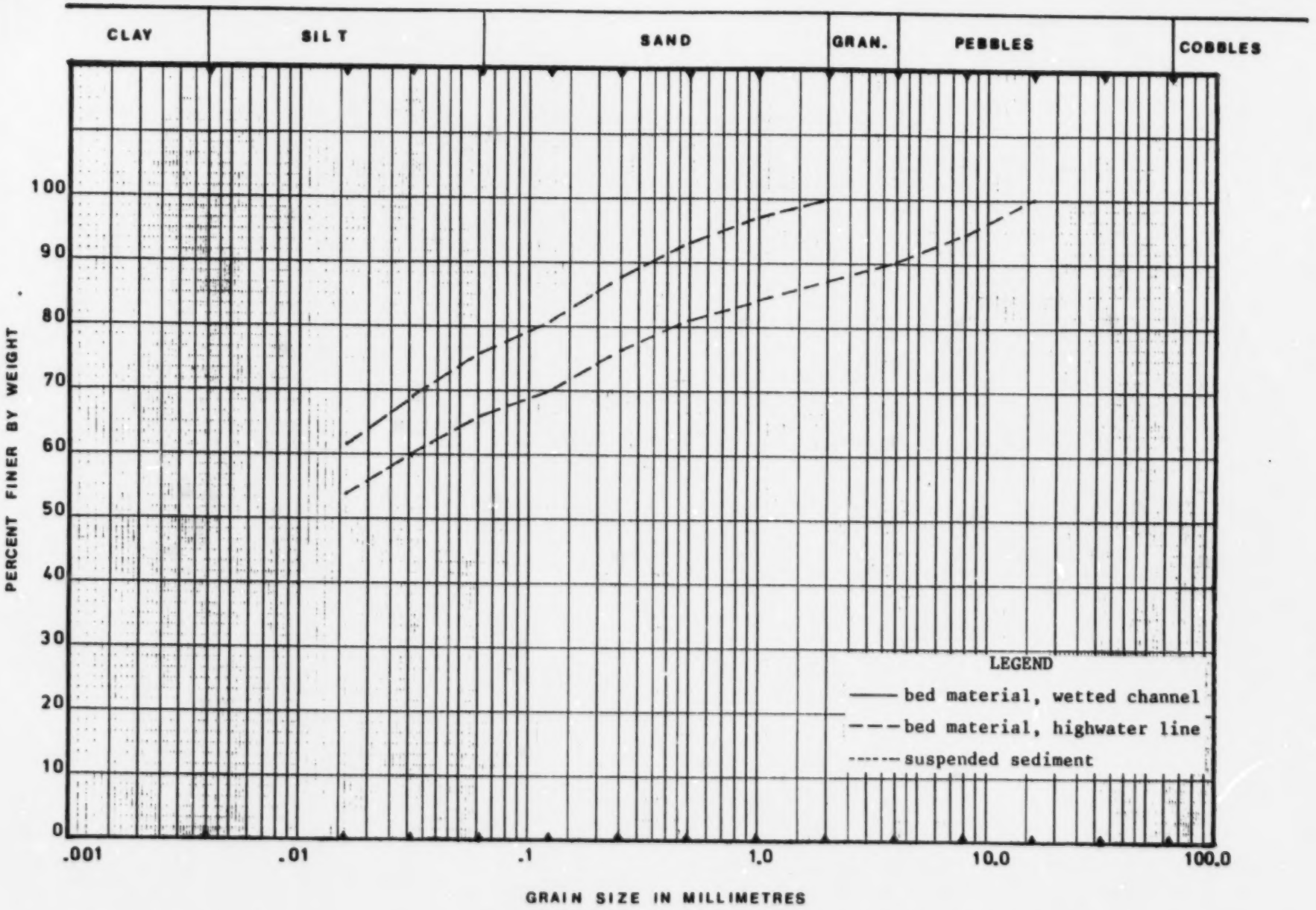

Figure AIV-2: Comparison of complete and truncated bed material size distributions, Liard River near the Mouth, 1973. Sample Location - HWLB.

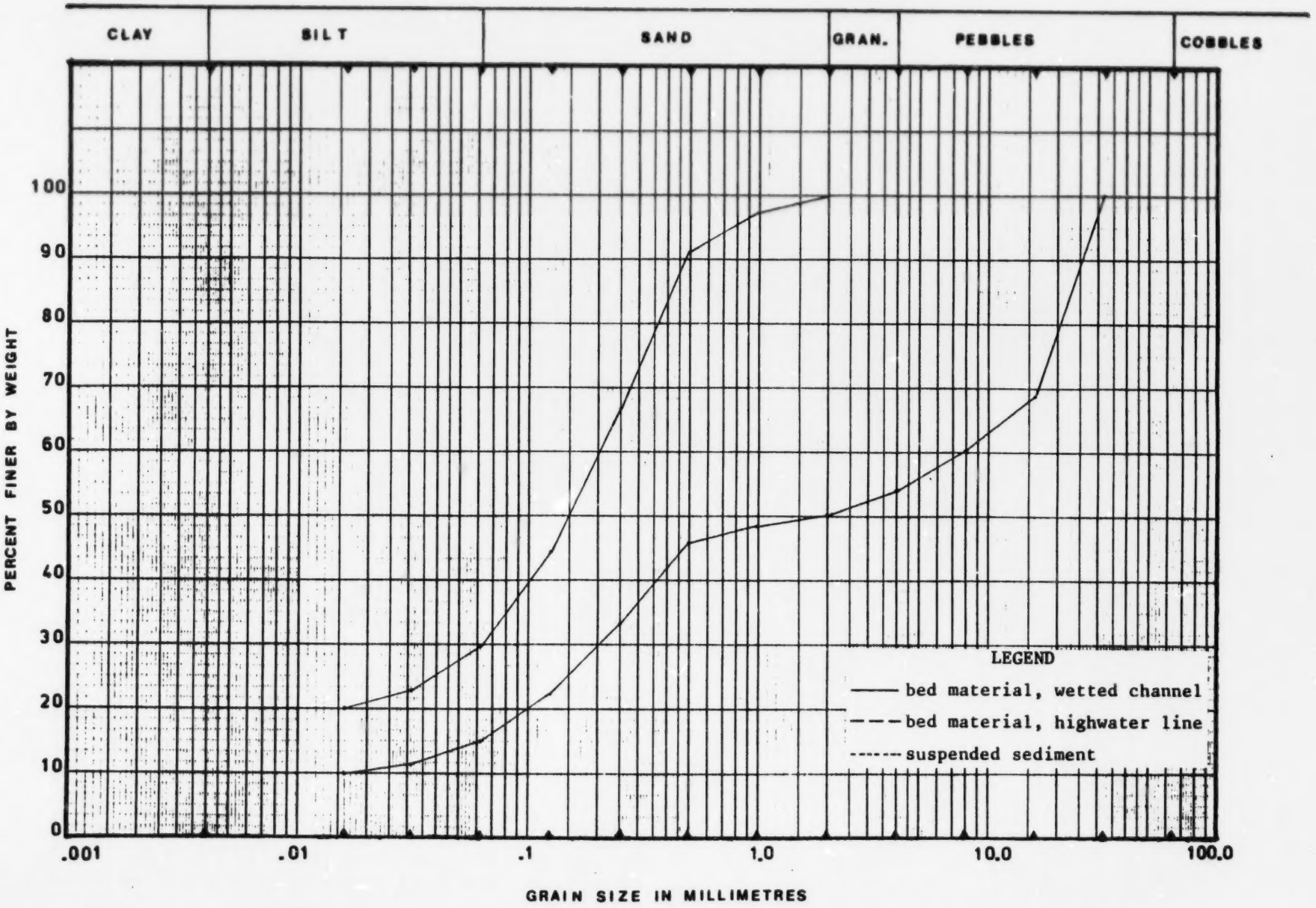

Figure AIV-3: Comparison of complete and truncated bed material size distributions, Liard River near the Mouth, 1973. Sample Location - WERB.

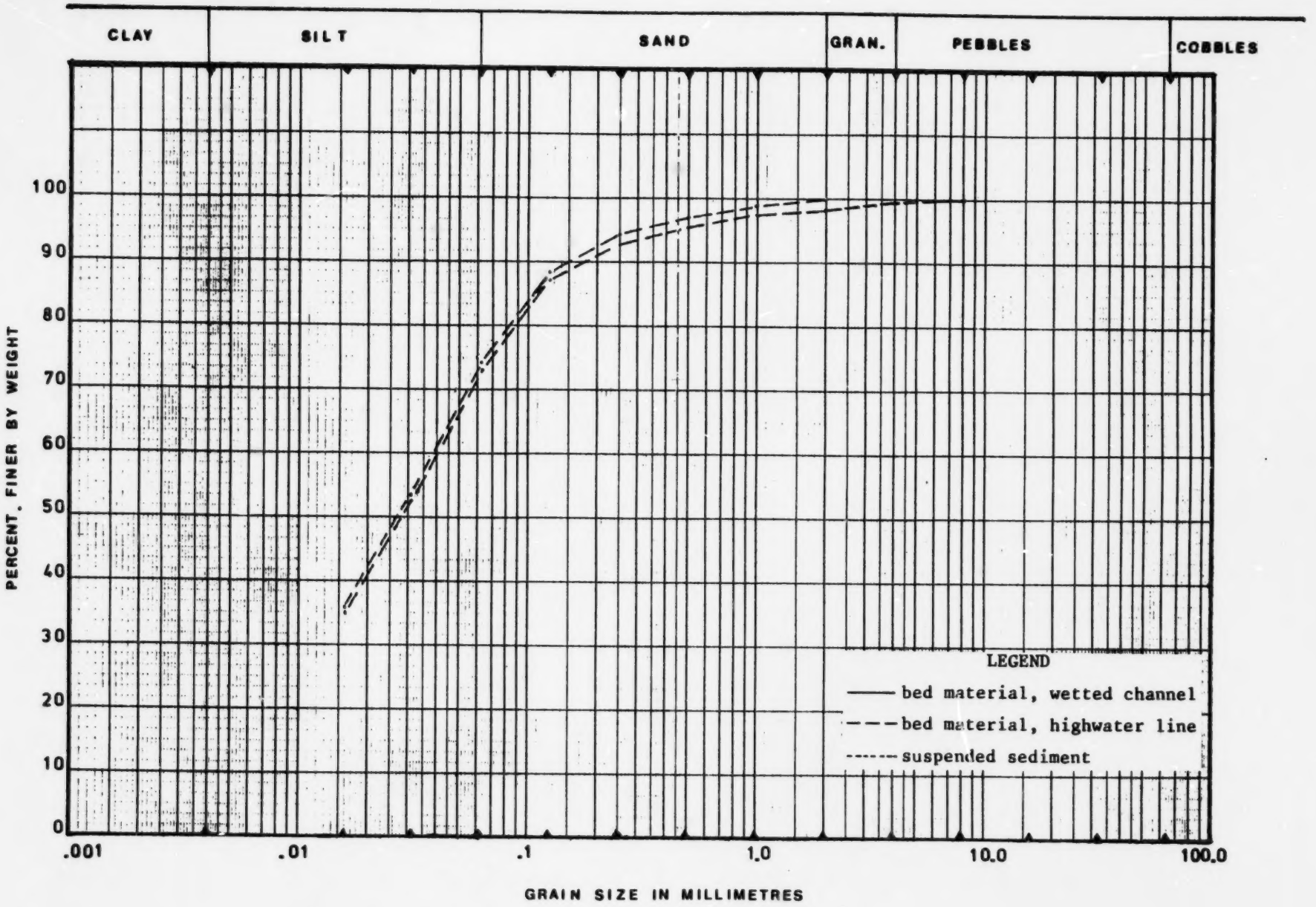

Figure AIV-4: Comparison of complete and truncated bed material size distributions, Liard River near the Mouth, 1973. Sample Location - HWRB.

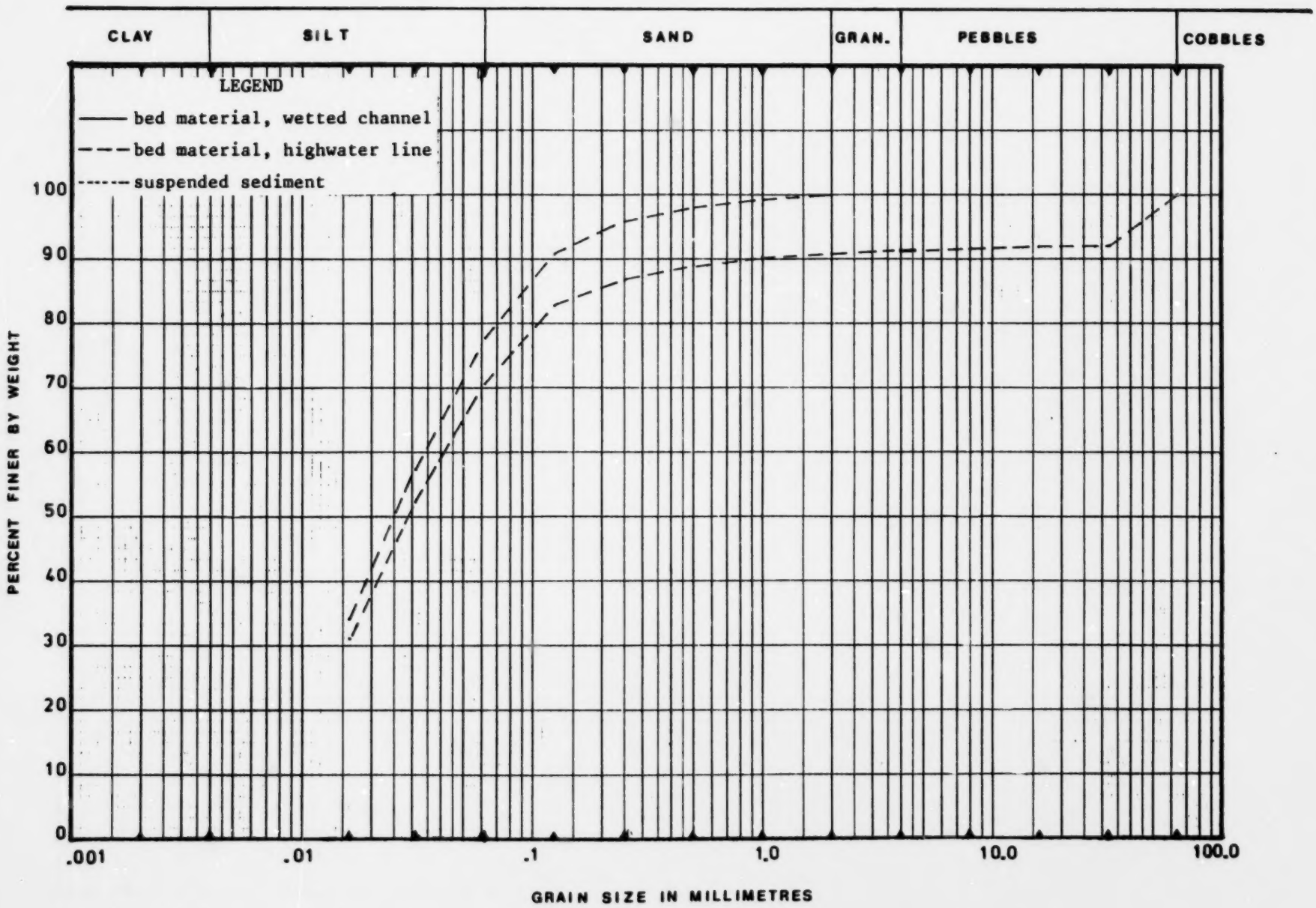

Figure AIV-5: Comparison of complete and truncated bed material size distributions, Liard River near the Mouth, 1974. Sample Location - HWRB.

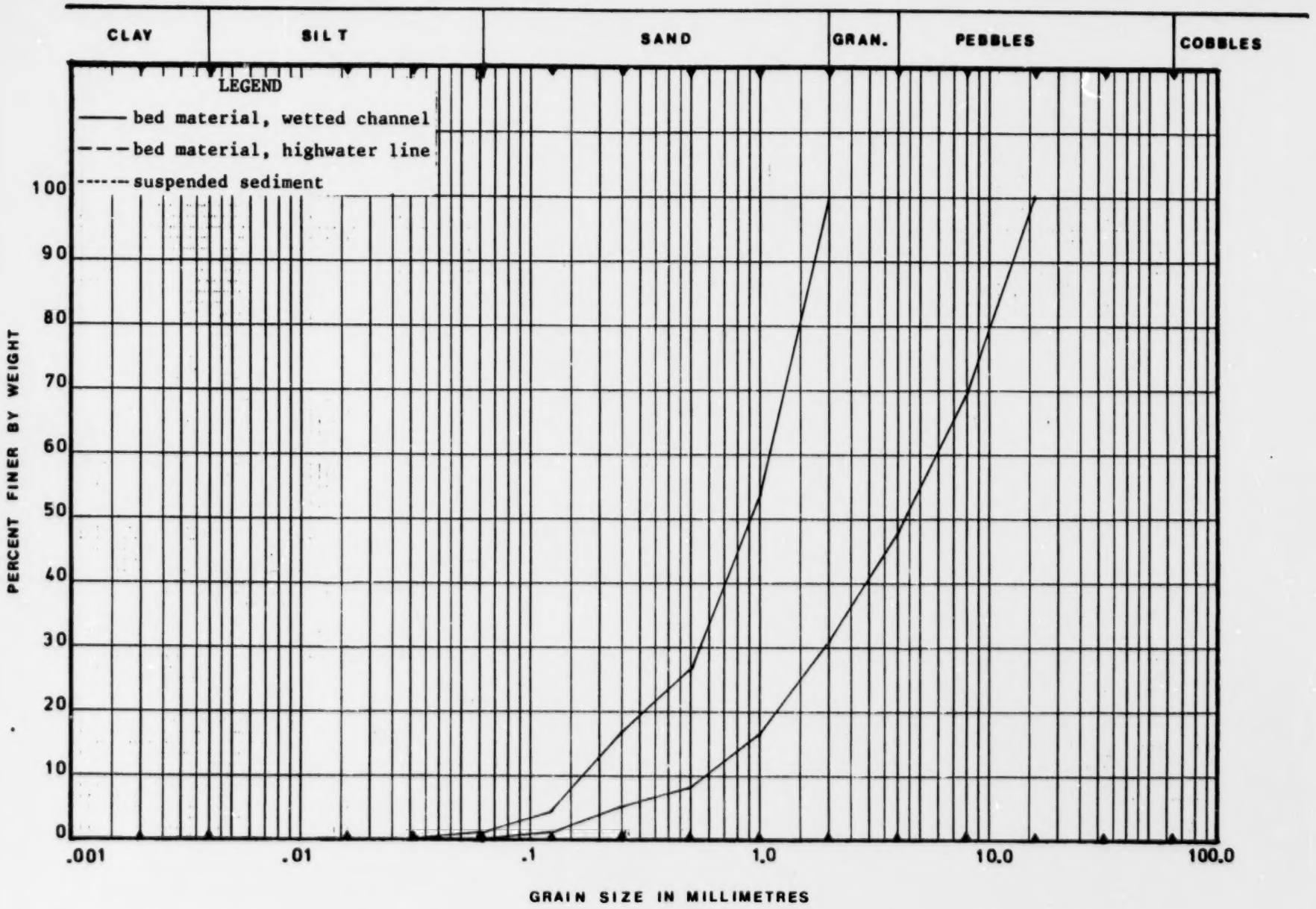

Figure AIV-6: Comparison of complete and truncated bed material size distributions, Liard River near the Mouth, 1974. Sample Location - #94

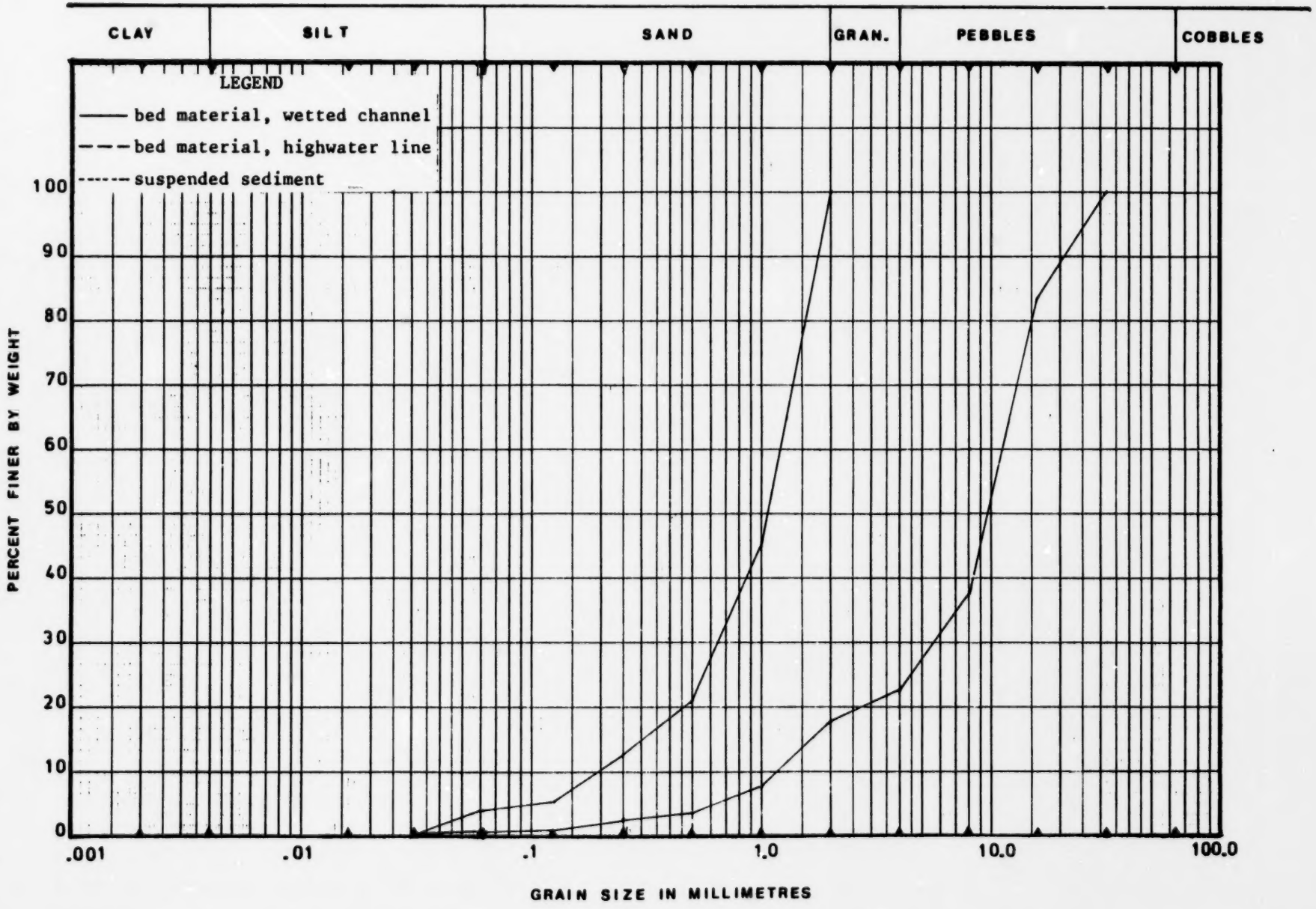

Figure AIV-7: Comparison of complete and truncated bed material size distributions, Liard River near the Mouth, 1974. Sample Location - #194.

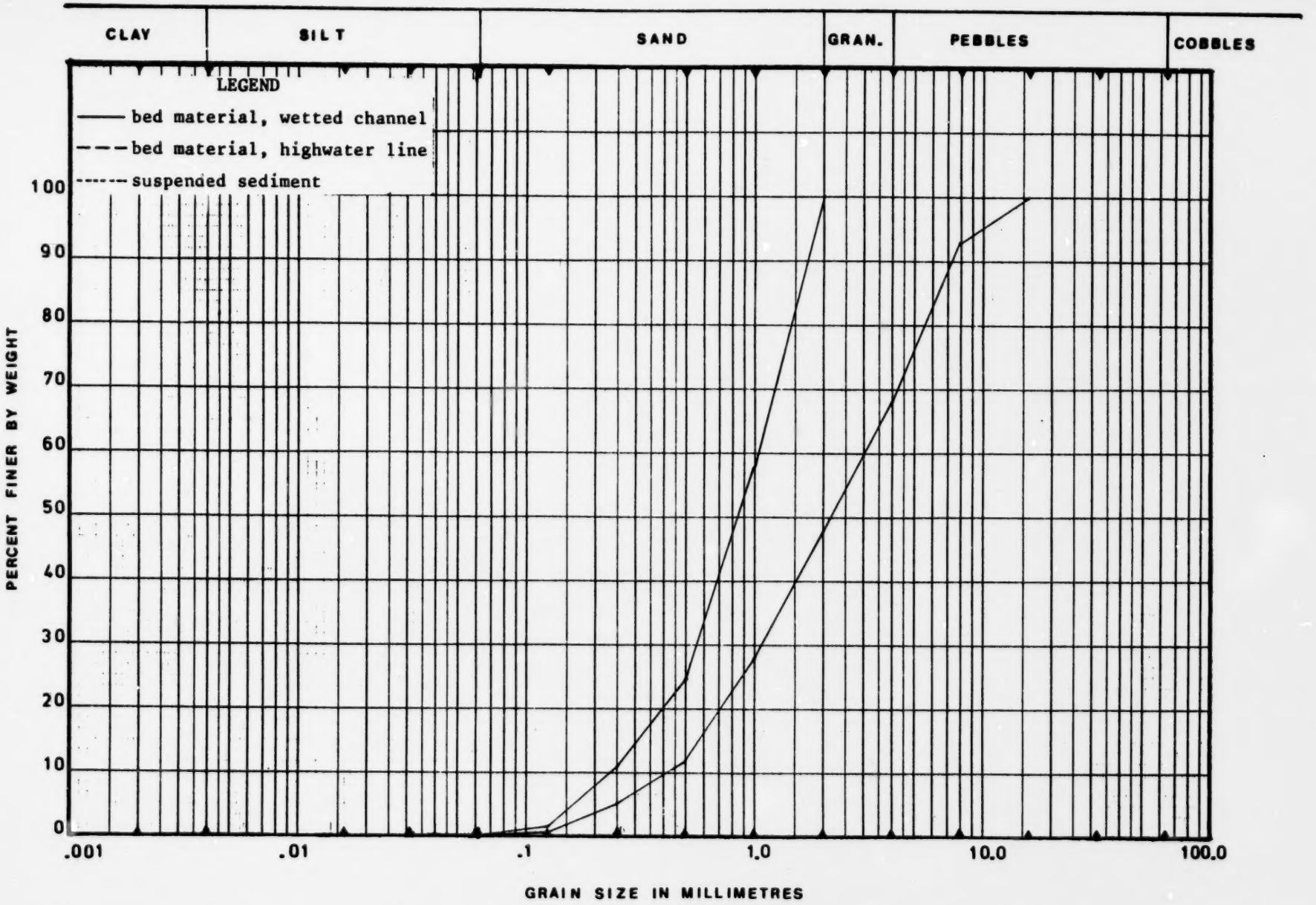

Figure AIV-8: Comparison of complete and truncated bed material size distributions, Liard River near the Mouth, 1974. Sample Location - #296.

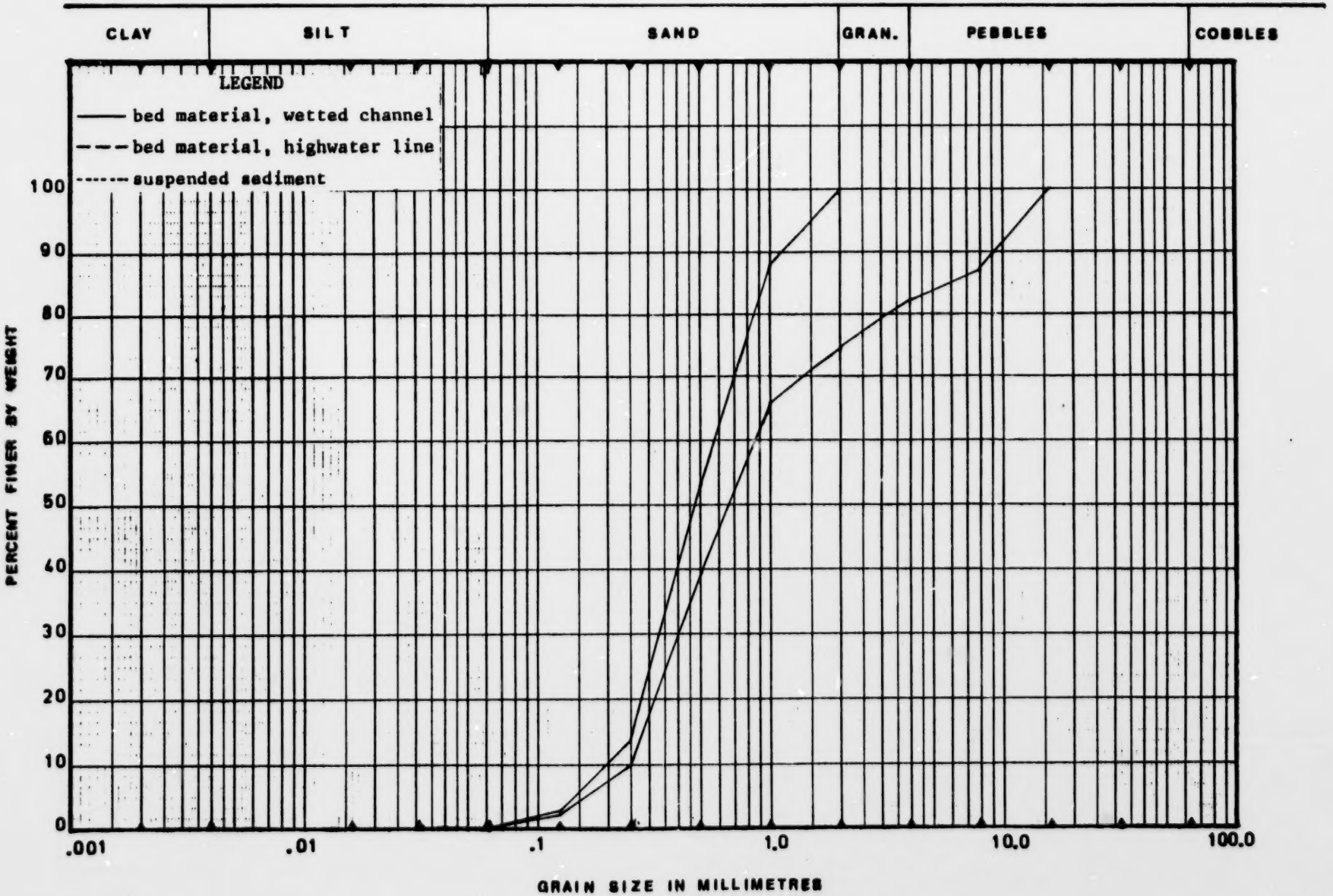

Figure AIV-9: Comparison of complete and truncated bed material size distributions, Liard River near the Mouth, 1974. Sample Location - #587.

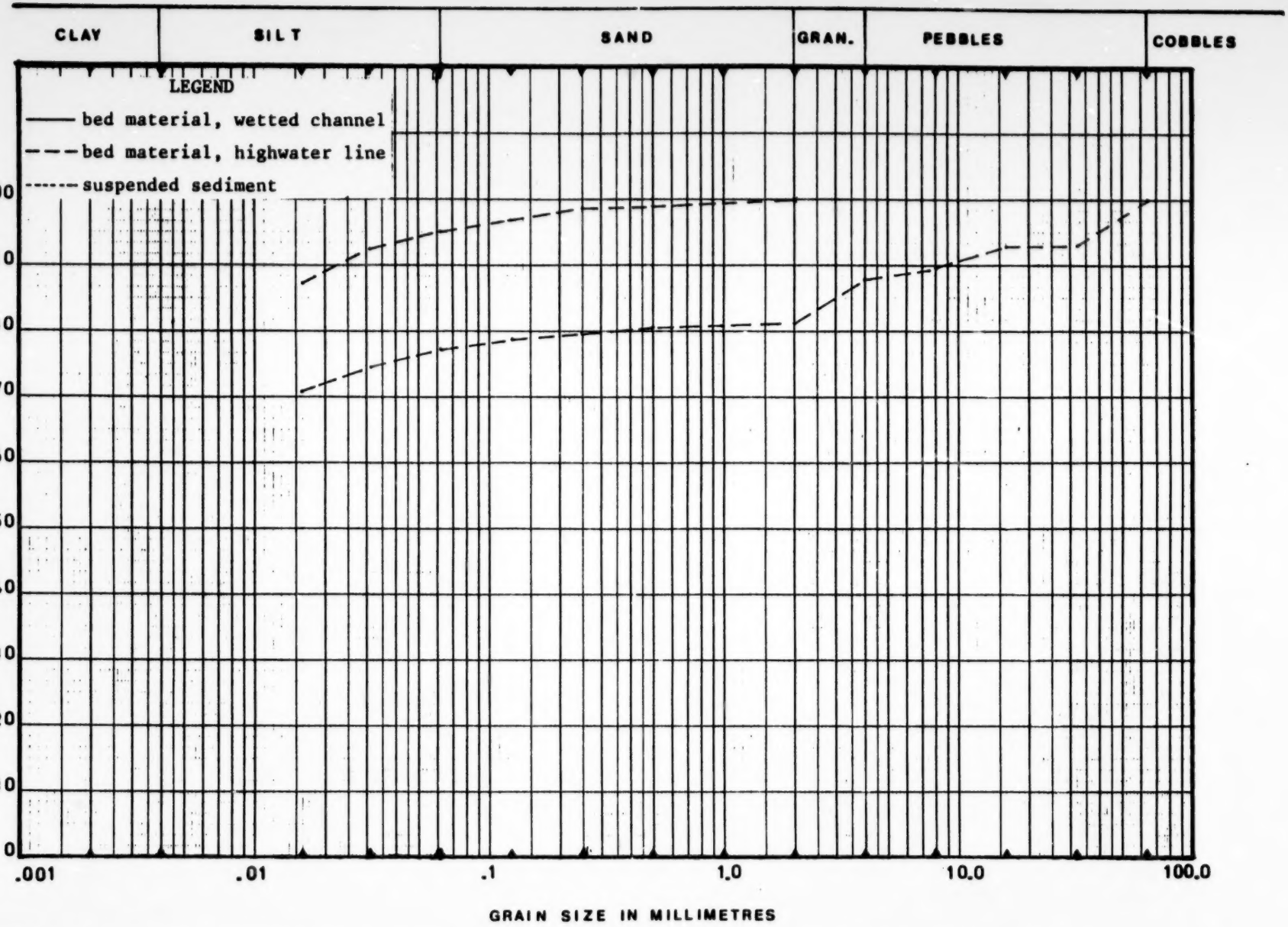

Figure AIV-10: Comparison of complete and truncated bed material size distributions, Liard River near the Mouth, 1974. Sample Location - HWLB.

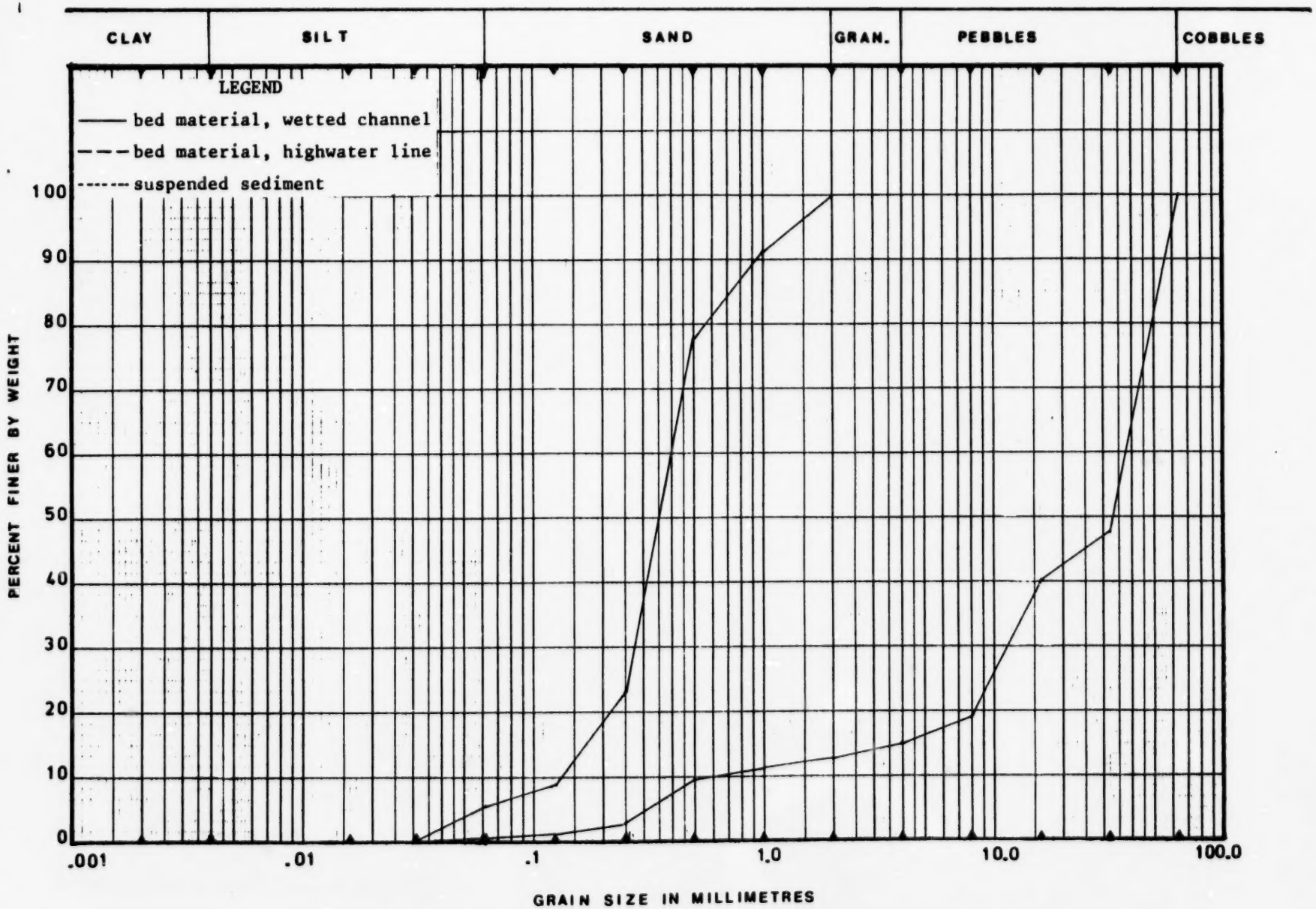

Figure AIV-11: Comparison of complete and truncated bed material size distributions, Mackenzie River above Liard River, 1974. Sample Location - #80.

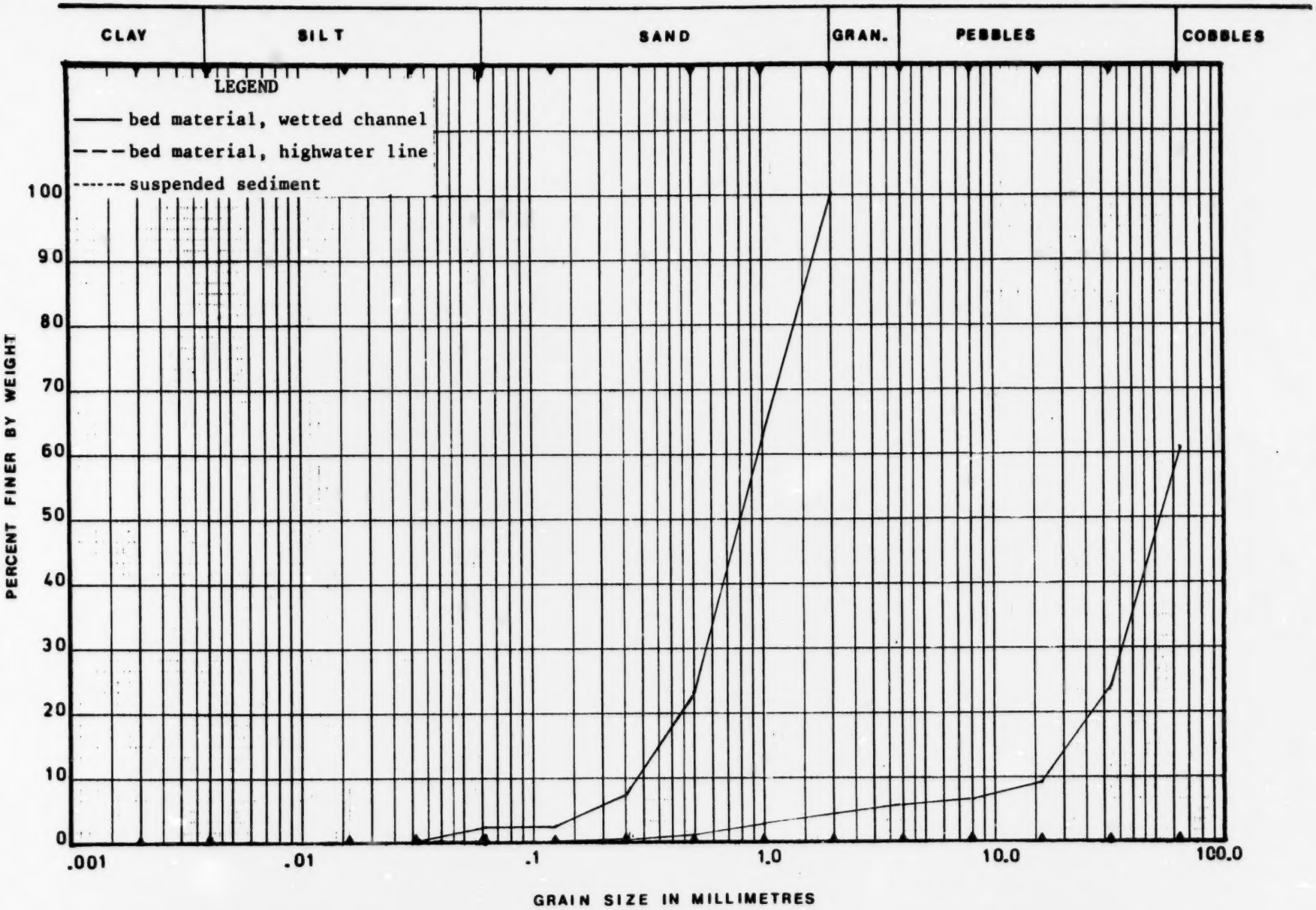

Figure AIV-12: Comparison of complete and truncated bed material size distributions, Mackenzie River above Liard River, 1974. Sample Location - #380.

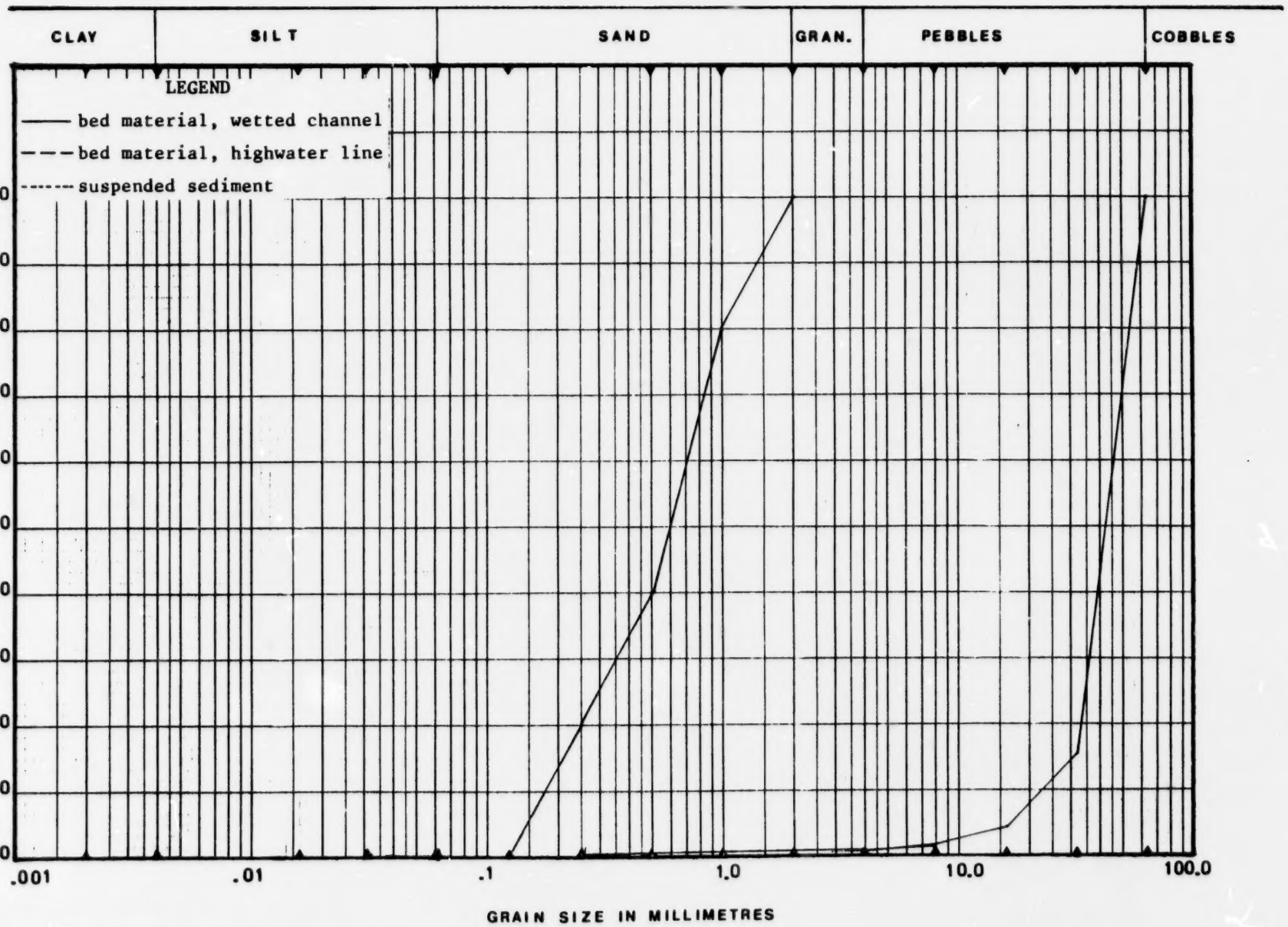

Figure AIV-13: Comparison of complete and truncated bed material size distributions, Mackenzie River above Liard River, 1974. Sample Location - #530.

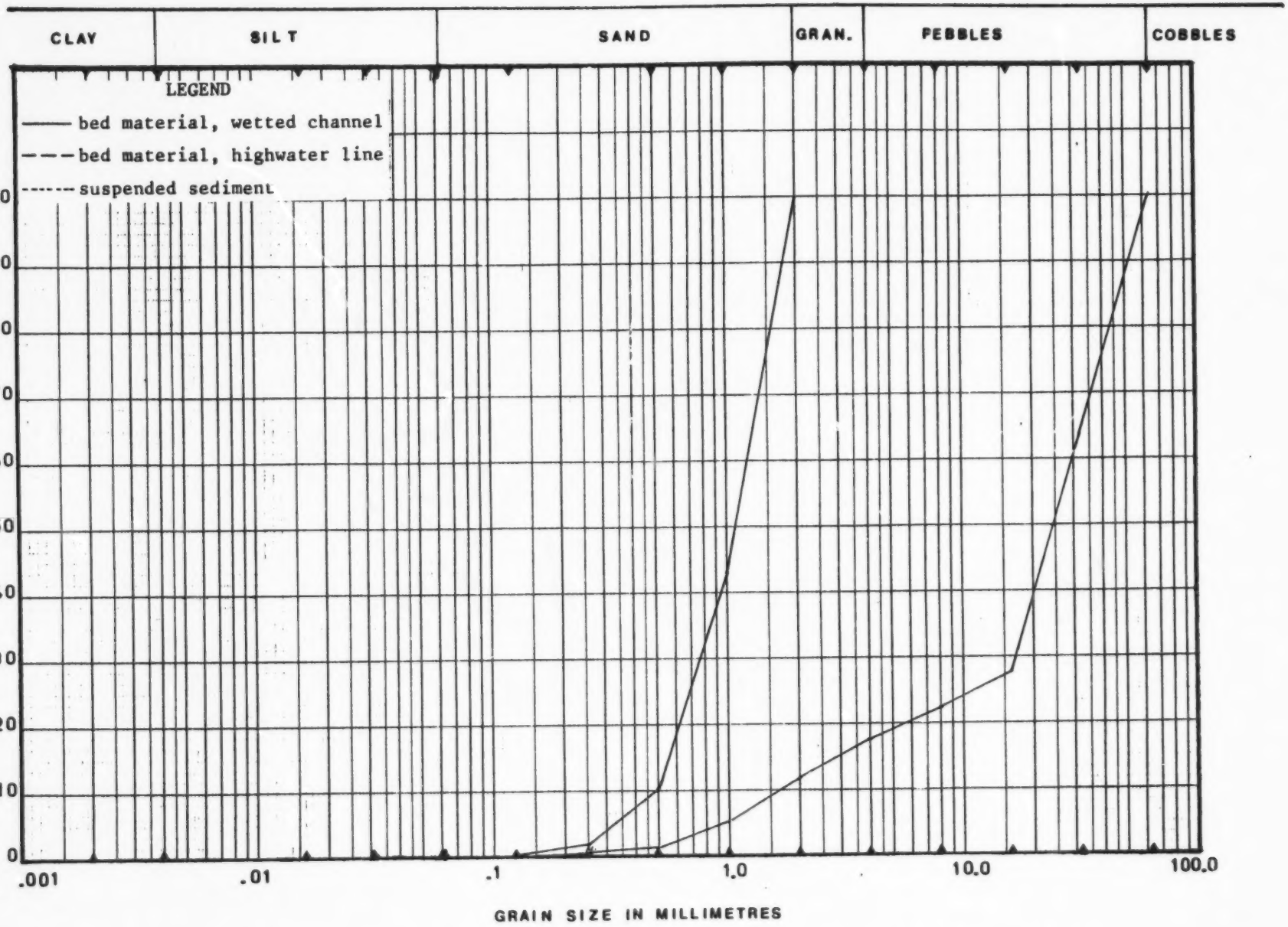

Figure AIV-14: Comparison of complete and truncated bed material size distributions, Mackenzie River above Liard River, 1974. Sample Location - #690.

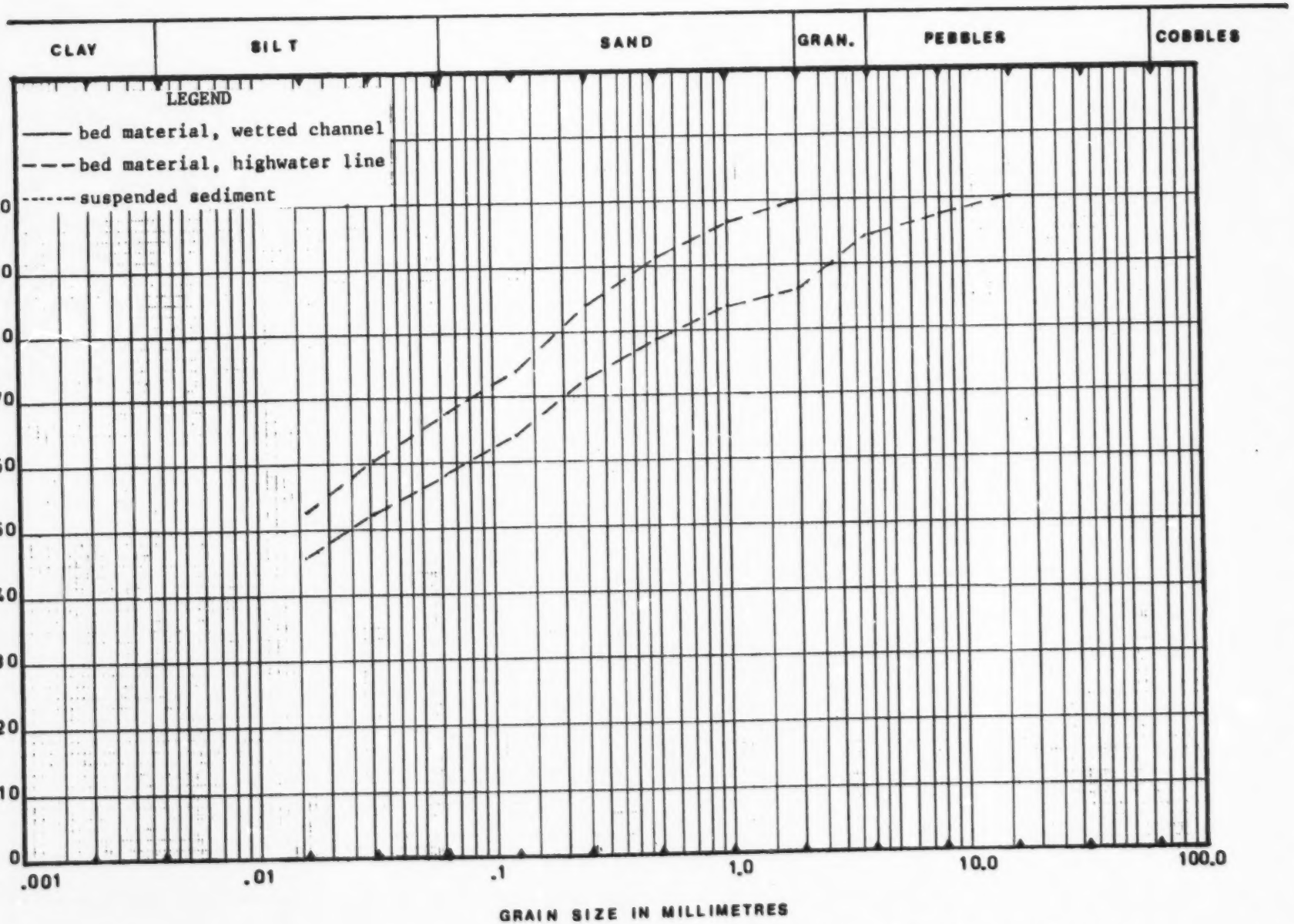

Figure AIV-15: Comparison of complete and truncated bed material size distributions, Mackenzie River above Liard River, 1974. Sample Location - HWLB.

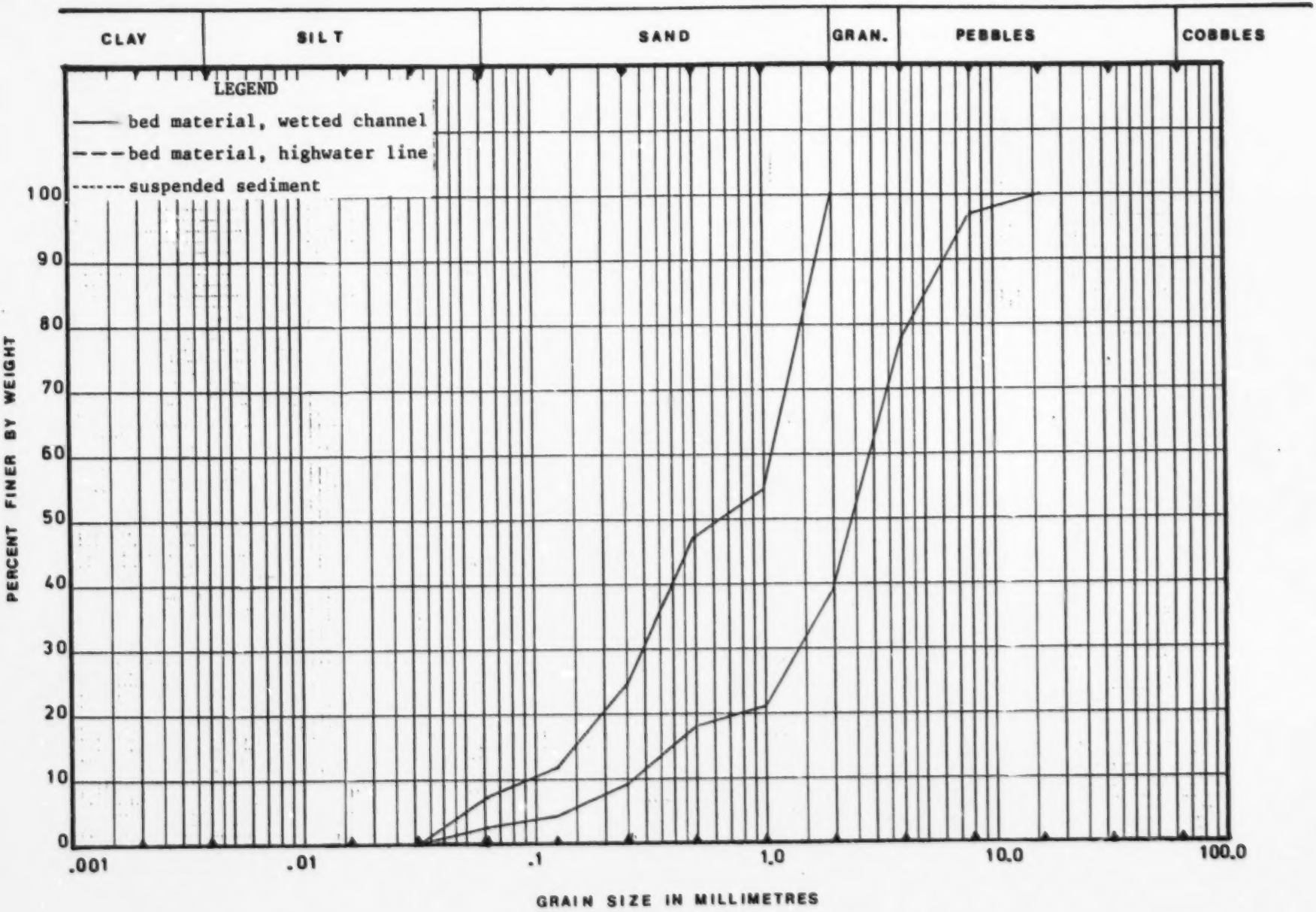

Figure AIV-16: Comparison of complete and truncated bed material size distributions, Mackenzie River above Arctic Red River, 1973. Sample Location - LBJ.

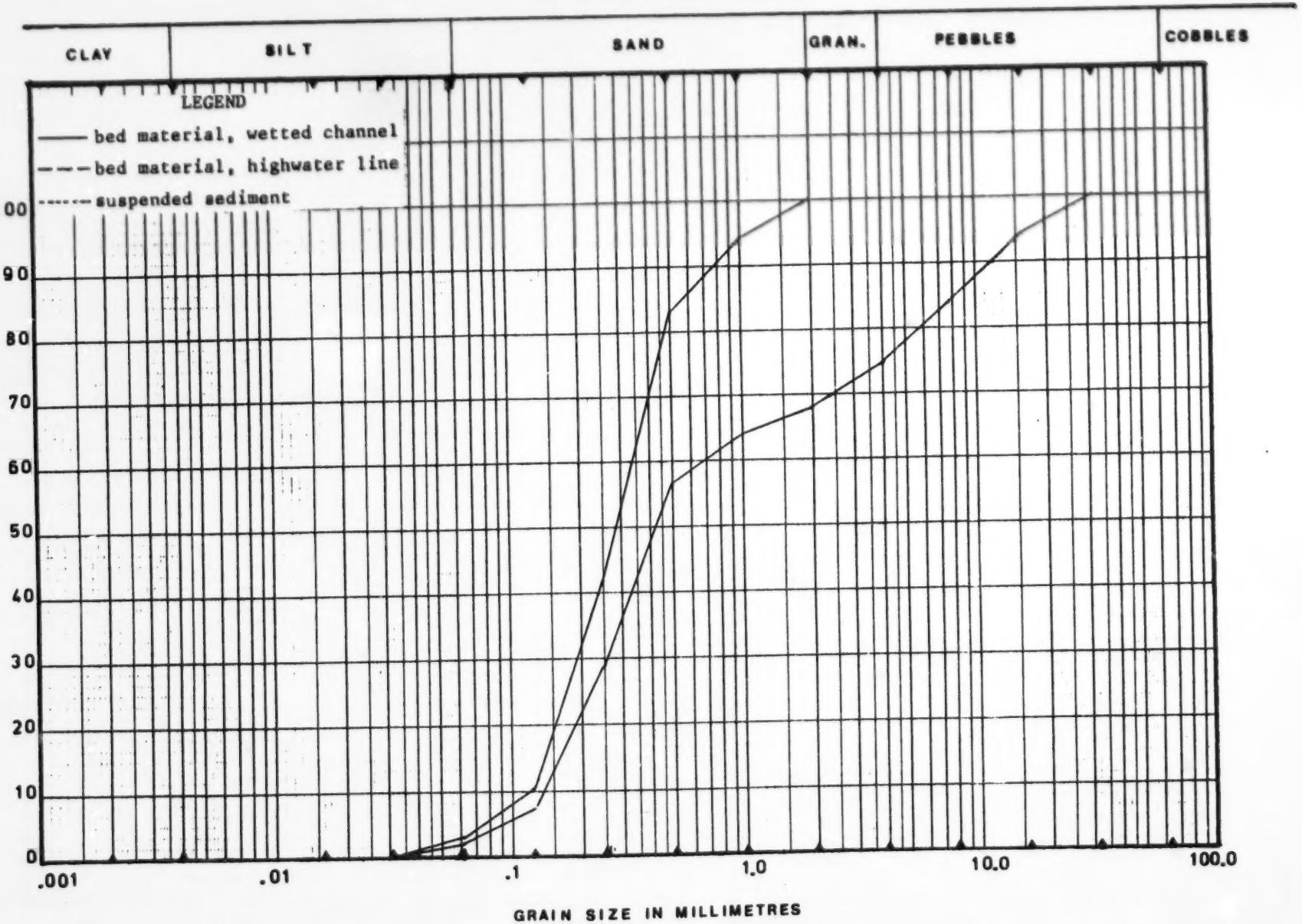

Figure AIV-17: Comparison of complete and truncated bed material size distributions, Mackenzie River above Arctic Red River, 1973. Sample Location - RBJ.

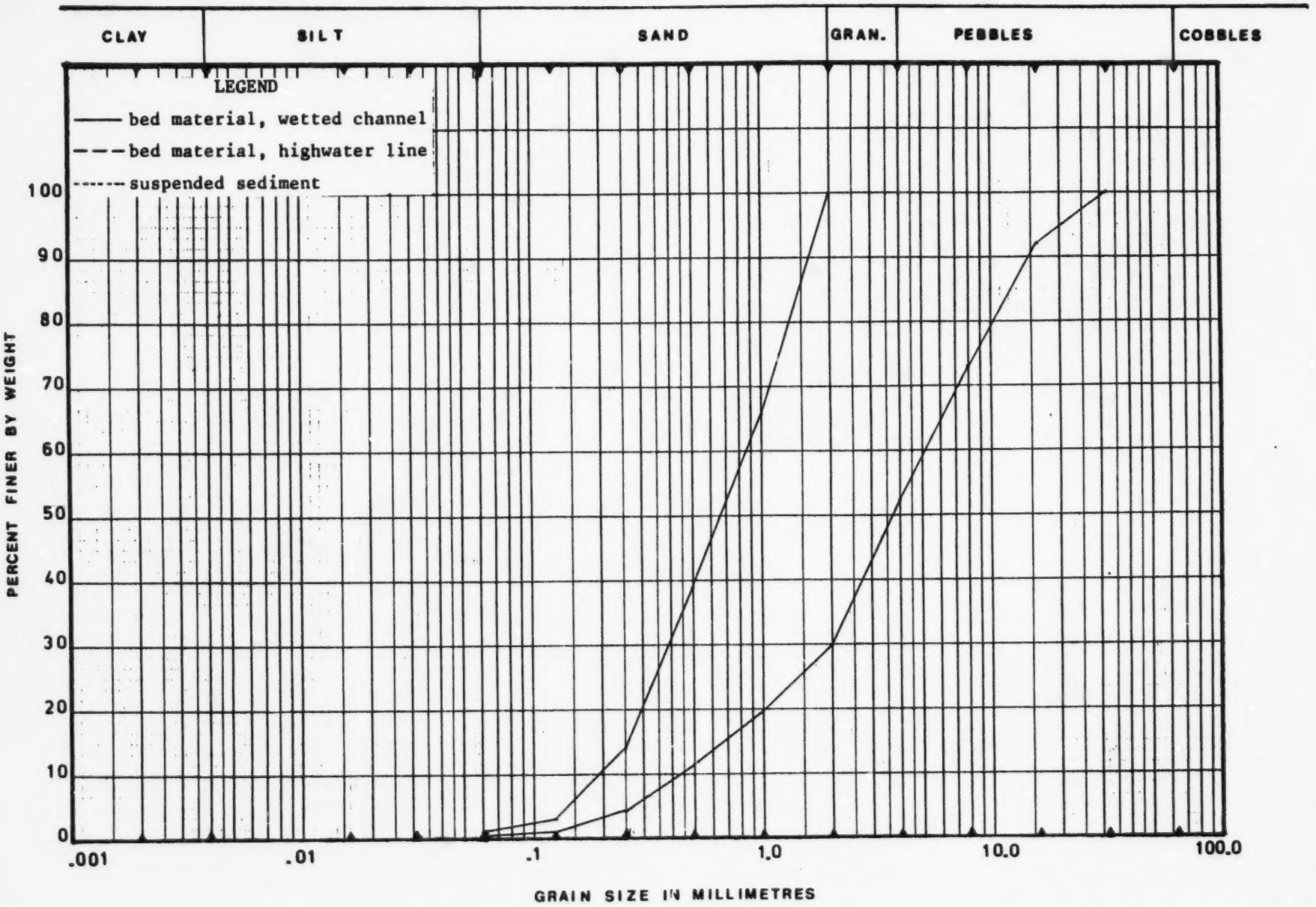

Figure AIV-18: Comparison of complete and truncated bed material size distributions, Mackenzie River above Arctic Red River, 1973. Sample Location - LBS.

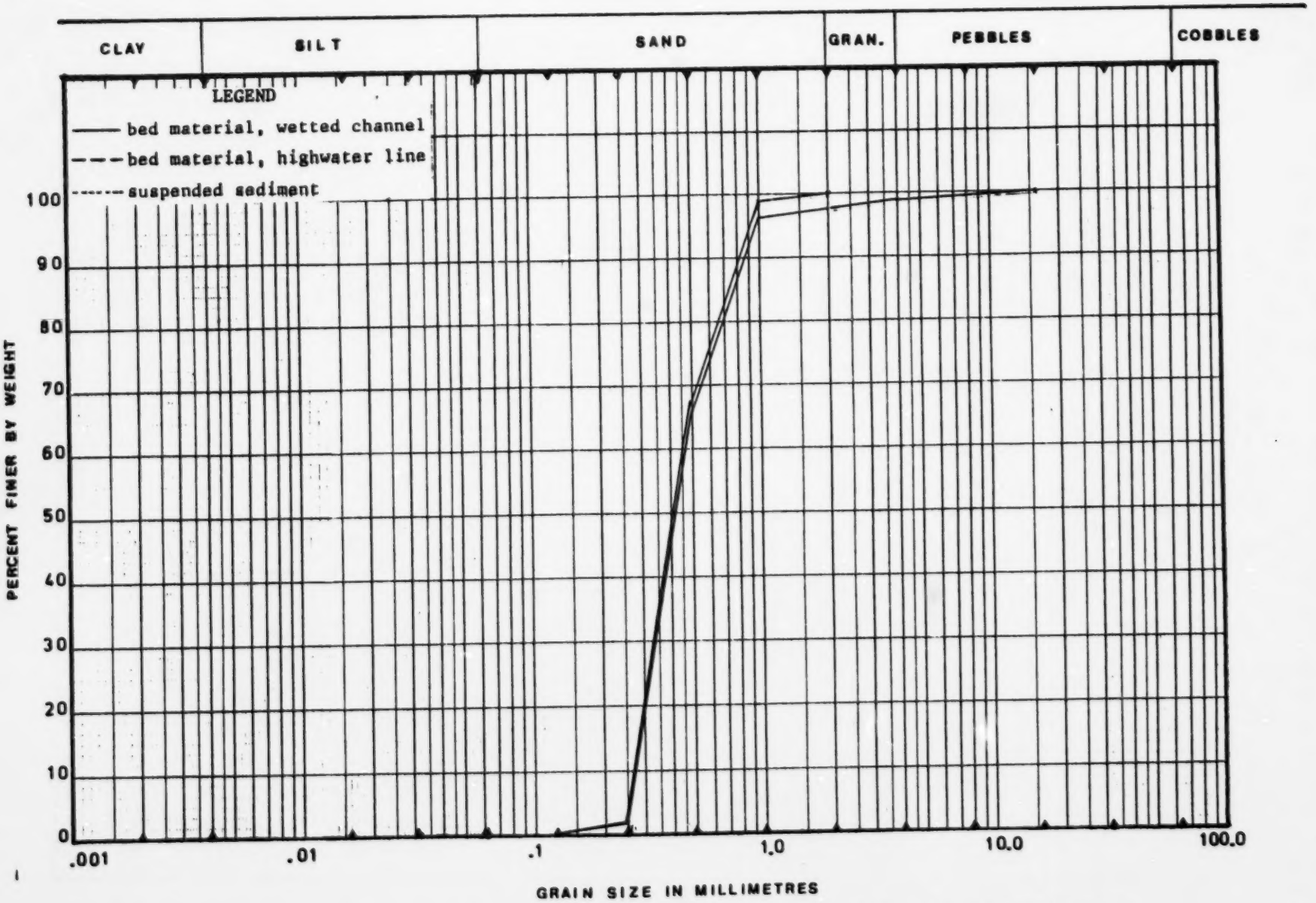

Figure AIV-19: Comparison of complete and truncated bed material size distributions, Mackenzie River above Arctic Red River, 1974. Sample Location - #2713.

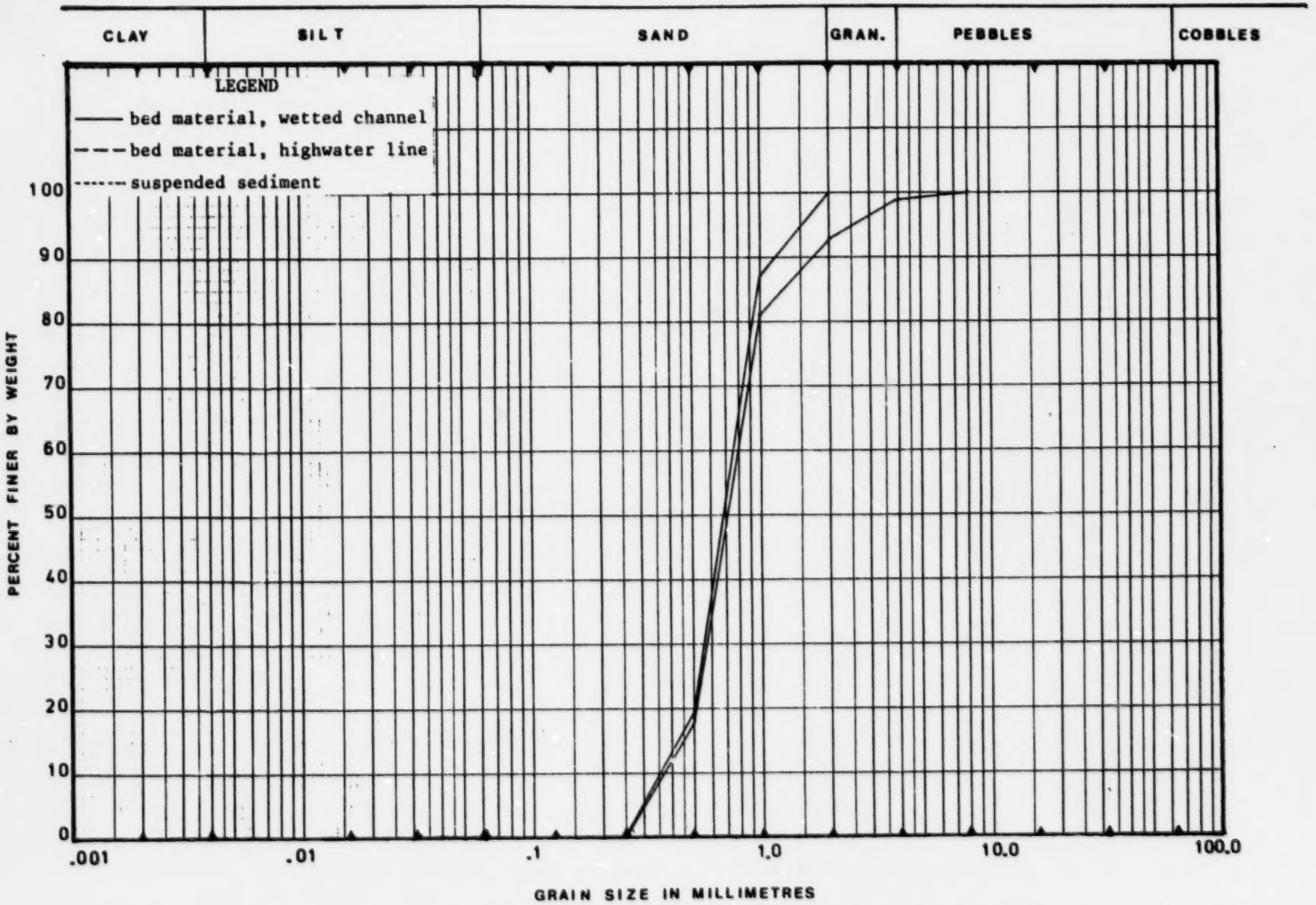

Figure AIV-20: Comparison of complete and truncated bed material size distributions, Mackenzie River above Arctic Red River, 1974. Sample Location - #3284.

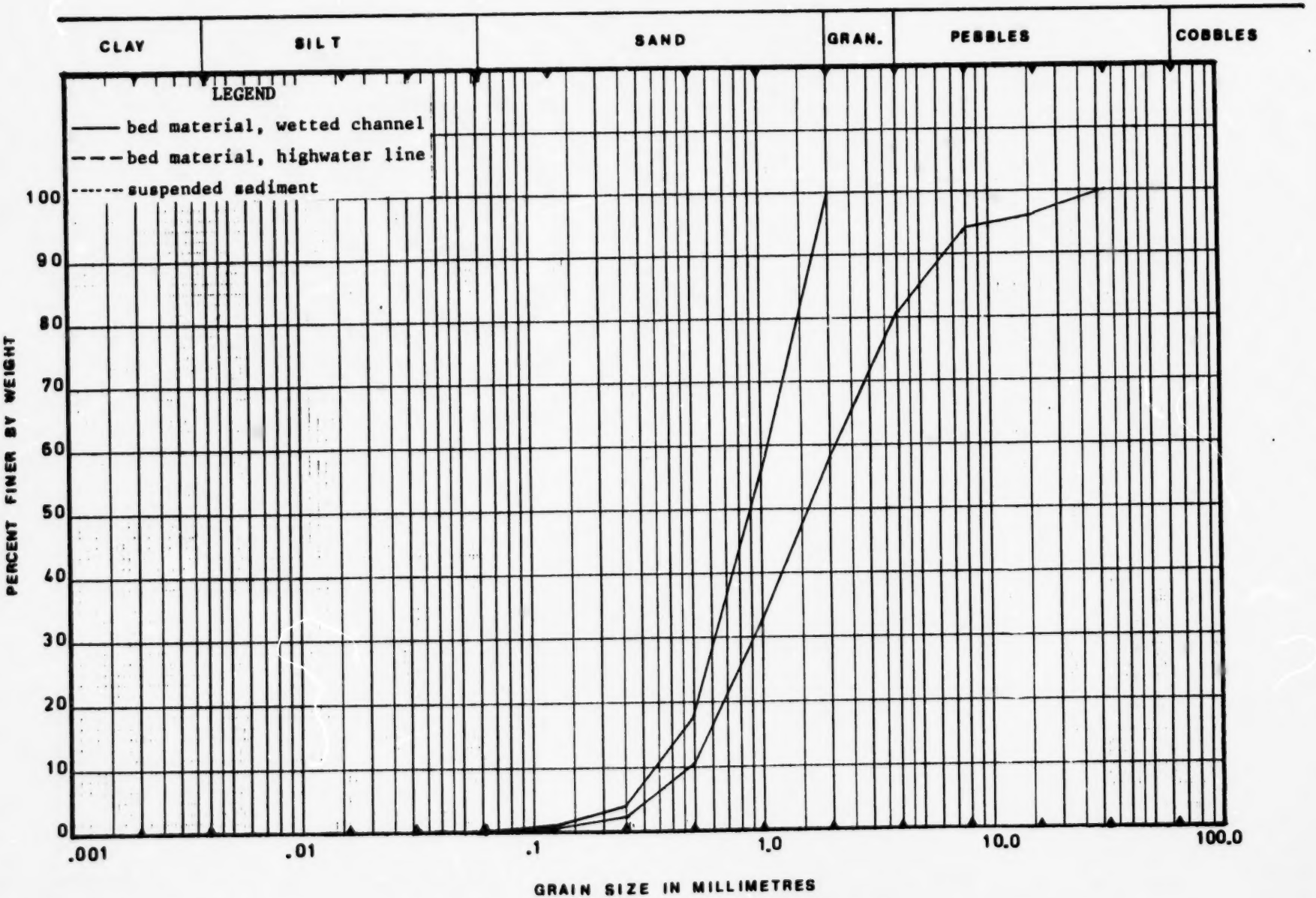

Figure AIV-21: Comparison of complete and truncated bed material size distributions, Mackenzie River above Arctic Red River, 1974. Sample Location - LB.

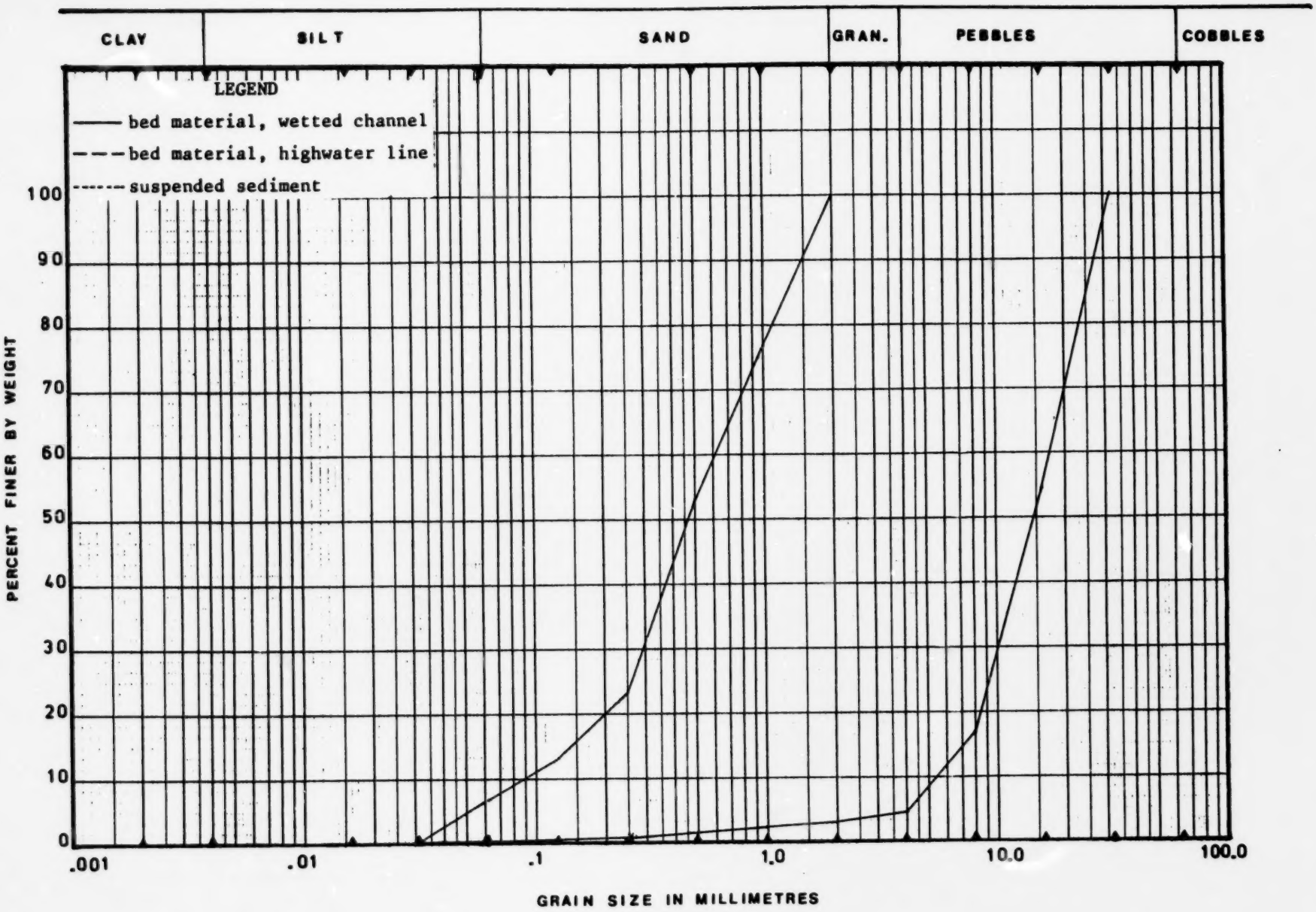

Figure AIV-22: Comparison of complete and truncated bed material size distributions, Mackenzie River above Arctic Red River, 1975. Sample Location - #124.